AN ANALYSIS OF UNCERTAINTY OF POINT AND NON-POINT SOURCE LOADING ON EUTROPHICATION ON A DOWNSTREAM RESERVOIR

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RESERVOIR

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CHAPTER I

INTRODUCTION

The proposed discharge of treated wastewater effluent by Fayetteville, Arkansas into Mud Creek, a tributary of Clear Creek which flows into the Illinois River approximately 90 miles above the headwaters of Lake Tenkiller Ferry concerned State of Oklahoma Health Officials. The main concern focused on the increased eutrophication potential for Lake Tenkiller and the Illinois River.(1) Figure 1 is a plan of the Illinois River Basin.(2)

Historically, accelerated rates of eutrophication of lakes have been attributed to increases in the amounts and types of nutrients discharged into the upstream watershed. If left unchecked the abundance of nutrients may lead to many undesirable water quality problems.(3) While eutrophication is a natural process it has been shown to increase dramatically in the presence of uncontrolled point and non-point source discharges of macro and trace nutrients. Generally, the accepted control approach has been to remove either nitrogen or phosphorus from waters draining into lakes and reservoirs. This is normally determined by the ratio of nitrogen to phosphorus. If the nitrogen to phosphorus ratio (N:P) in the lake is less than 5, algal growth will be nitro-

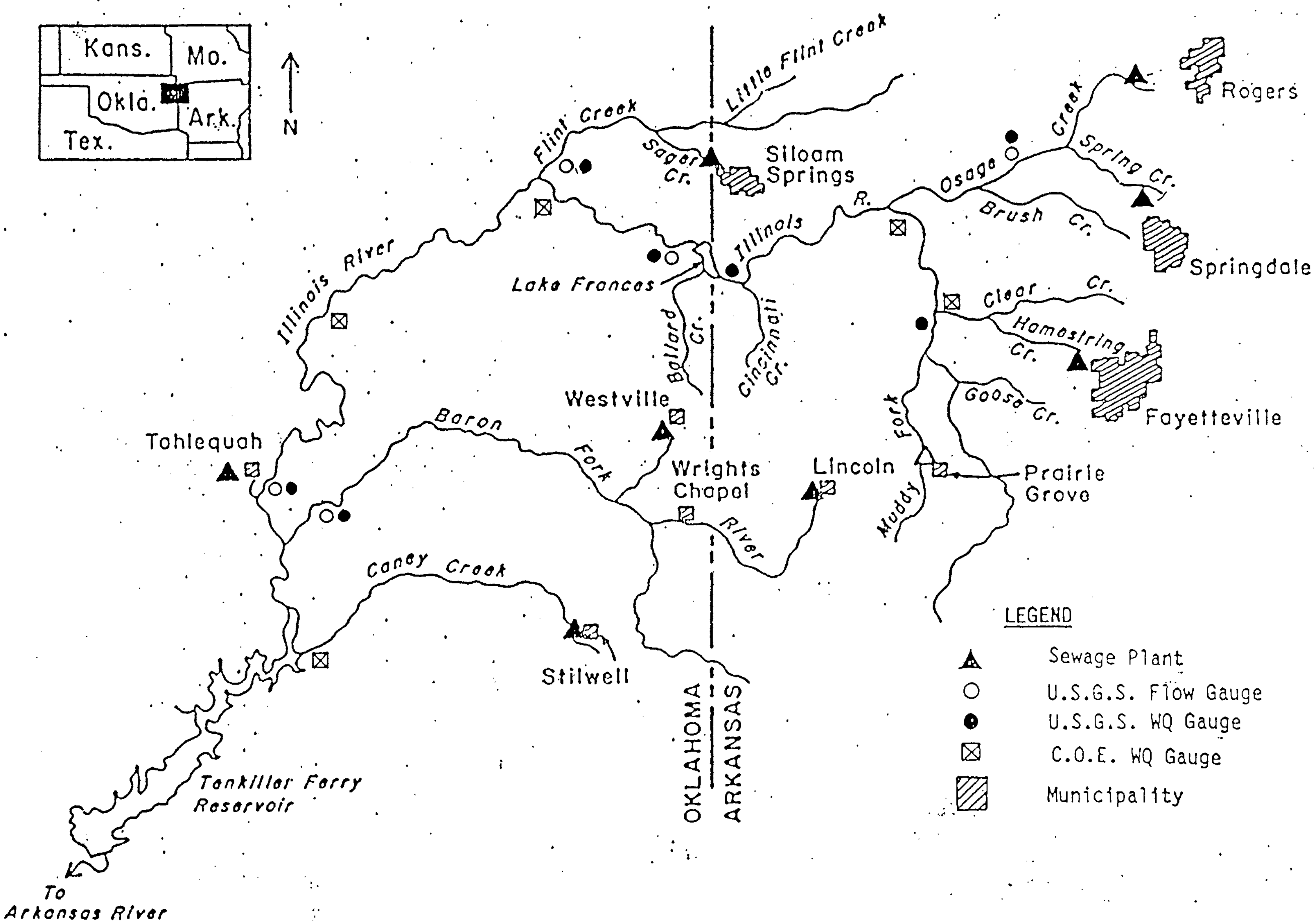


Figure 1. Plan of the Illinois River Basin and Lake Tenkiller

gen limited, if the ratio is between 5 and 10, either or both may control eutrophication, if the N:P is greater than 10, phosphorus should control eutrophication.(4)

Historical water quality data for the Tahlequah, Oklahoma water quality gauge on the Illinois River, which is directly above the confluence with Lake Tenkiller, have a N:P of 15:1.(5) The total nitrogen and phosphorus distributions at this location are shown in Figure 2. Based on these data Lake Tenkiller was considered phosphorus limited. Subsequent analysis was restricted to the role played by phosphorus in identifying possible future impacts.

Model Selection

Analysis of water quality in large watersheds is complicated by the lack of availability of risk assessing computer models. The types of models considered for this analysis were the dynamic wave and the static or steady-state model. The dynamic wave is a time varying code which utilizes deterministic coding and channel geometry data. These data were unavailable from both the U.S. Army Corps of Engineers and the Federal Emergency Management Administration (FEMA) for the Illinois River. The steady-state models are time independent. These two models can be further categorized into total watershed models or channel codes. These types of models must be calibrated using extensive land use and river data. Much of the data were unobtainable or required extensive, long term field sampling. The calibration of these

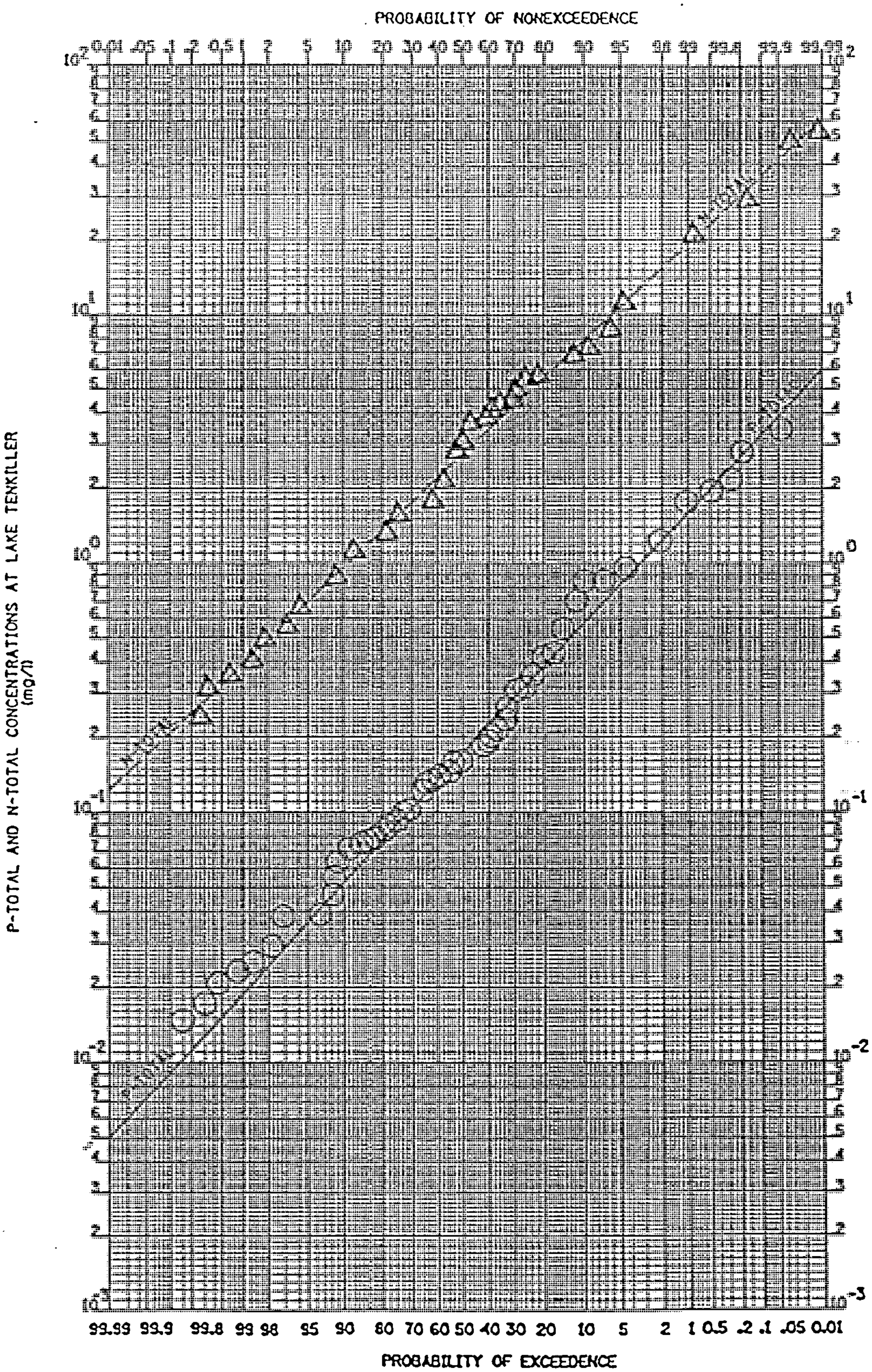


Figure 2. Concentration Probability for Total Phosphorus and Total Nitrogen at Tahlequah, Oklahoma Water Quality Gauge

models to the 1600 square mile Illinois River watershed was considered infeasible for this task. The dynamic wave type model is a time-dependent model while the static steady-state model is time-independent. Eutrophication has a broad time horizon and instantaneous real-time loads are not required justifying a longer time step and the limited use of time independent techniques. Table I summarizes the main features of the water quality models considered for use in this effort. A method was presented which utilized long term water quality monitoring data and a steady-state, low flow channel model. These data were used to develop probability density functions (PDFs) which were subsequently accessed randomly to define a level of probability for a given phosphorus input. The Fayetteville treated effluent distribution at low flow was then used with the historical data base which incorporates event driven phosphorus throughout the watershed.

The Vollenweider eutrophication evaluation technique was used as a parametric indicator to examine the effects of the addition of treated Fayetteville effluent as well as those resulting from the respective removal options on eutrophication potential in Lake Tenkiller. The Vollenweider graph was used as a method of graphical comparison of the various options examined in this study. This method considers lake hydraulics and operation as well as the phosphorus loading into lakes. The Vollenweider graph provides a visual representation of the calculated values and is a widely accepted eutrophication indicator for lakes.(5)

TABLE I

SUMMARY OF WATER QUALITY MODELS CONSIDERED FOR ILLINOIS RIVER BASIN EUTROPHICATION ANALYSIS (6,7)

Water Quality Model Data	Water Quality Models QUAL2EU	CE-QUAL-R1V1	CE-QUAL-R1	HSPF	CE-QUAL-W2
Responsible Agency	U.S.E.P.A	C.O.E-W.E.S.	C.O.E.-W.E.S.	U.S.E.P.A.	C.O.E.-W.E.S.
Description	-Steady state hydraulic -Dynamic nutrient -1D longitudinal -Stochastic	-1D dynamic hydraulic -Dynamic nutrient -Time varying -Deterministic	-1D vertical reservoir -Stochastic	-Watershed model -Deterministic	-2D dynamic hydaulic -Dynamic nutrient -Stochastic
Monte Carlo Opt. Available	Yes	No	Yes	No	No
Event or Risk Oriented	Risk	Event	Risk	Event	Risk
Data Above Agency Historical Data	-Water quality rate coeffic.	-Physical & cross section geometry river data. -Water quality coeffic.	-Outlet configur. -Water quality rate coeffic.	-Extensiv. unpublish. empirical data.	-Tidal bound. conditions -Water quality rate coeff.
Normal Application	-Conditions w/o rapidly varying flow.	-Resolut. of time varying condit. -Hydropower operat.	-Studies requir. 2D resolution.	-Land use changes -Ungauged watershed.	-Studies need. 2D resolut. in reservrs.
Output	-Probability functions -Longitud. profiles	-Time-series plots -Single values at selected nodes.	-Longit. and verical profls. -Statstcl data.	-Time-series plots. -Single value at selected locations.	-2D plots. -Statistcl data. -Time-series plots.
Availability For Microcomputer	Yes	No	No	Yes	No

Experimental

Data Collection

Data were obtained and compiled from various state and federal agencies. Table II has a listing of the agencies and the data available from those agencies. There were a number of studies available which provided the water quality rate coefficients for use in the computer simulations.

Model Selection

The model selected was the QUAL2E-UNCAS model issued by the USEPA.(23) This model was chosen for the following reasons;

-wide use and acceptance.

-uncertainty assessing capabilities.

-acceptance of available historical data.

-uncertainty analysis option.

One of the uncertainty options available in the QUAL2E-UNCAS water quality model is the Monte Carlo simulations technique. The Monte Carlo simulation technique is a method of operating a complex system that contains random variables. Input data are randomly sampled from non correlated distributions. QUAL2E-UNCAS accepts a stochastic input and utilizes deterministic coding to generate a probablistic output. Table III is a summary of the reach data used in the QUAL2E-UNCAS simulations. Table IV contains summary data describing the main tributaries to the Illinois River which were treated as point

TABLE II

AVAILABLE DATA SOURCES

Source	Location	Data Type	Year
United States Geological Survey (U.S.G.S.)(8)(9)	Oklahoma City, Oklahoma	-Drainage Areas	
		-Water Quality Gauges	1948-87
		-Discharge Data	1948-87
		-Velocity Data	
		-Stage-Discharge Data	
U.S. Army Corps of Engineers (10)	Tulsa, Okla. District	-Water Quality Gauges	1985-86
		-Tenkiller Pool Data	1952-Pr
		-Point and Non-Point Source Data	1985
United States Environmental Protection Agency (2)	Dallas, Texas	-Fayetteville NPDES Data	1985
		-Water Quality Parameters	1985
Oklahoma State Department of Health (11)(12)	Oklahoma City, Oklahoma	-Water Quality Data	1977-85
		-Point Source Data	1977-79
		-Non-Point Source Data	1977-79
Arkansas Department of Pollution Control (13)(14)	Little Rock, Arkansas	-Point Source Data	1985
		-Non-Point Source Data	1983-85
		-Water Quality Data	1985
		-Illinois River and Tributaries Studies	1985

TABLE III

REACH GAUGING DATA ILLINOIS RIVER DRAINAGE BASIN (12)

Reach No.	From*	Reach R.M.	To	R.M.	Stream Length (miles)	Drainage Area (sq. mi.)	Period Of Record	** N:P Ratio	Responsible Agency
1	Savoy, Ark.	133.8	Pedro, Ark.	124.6	8.2	167	1974-1987	20:1	U.S.G.S.
2	Pedro, Ark.	124.6	Siloam Sprngs Ark.	115.5	9.1	246	1985		C.O.E.
3	Siloam Sprngs Ark.	15.5	Watts, Ok.	106.2	9.3	635	1975-1981	8:1	U.S.G.S.
4	Watts, Ok.	106.2	Above Flint Crk. Confl.	94.0	12.2	232	1970-1985	14:1	U.S.G.S.
5	Above Flint Crk. Confl.	94.0	Combs Bridge, Ok.	72.0	22.0	552	1985		C.O.E.
6	Combs Bridge, Ok.	72.0	Tahlequah, Ok.	55.8	16.2	959	1985		C.O.E.
7	Tahlequah, Ok.	55.8	Lake Tenkiller Headwaters	35.0	19.2	651	1976-1985	15:1	U.S.G.S.

*Denotes gauge refered to for period of record, N:P ratio and responsible.
**U.S. Army Corps of Engineers gauges did not record total nitrogen therefore N:P ratio is not calculated.

source loads to the mainstem in the subsequent water quality simulations.(10)

Eutrophication Potential Analyses

Determination of Fayetteville Treated Effluent Distribution. The main goal of this effort was to determine the eutrophication impact on Lake Tenkiller. QUAL2E-UNCAS determined the phosphorus distribution under low flow conditions. The Fayetteville maximum phosphorus concentration used in this effort was at the National Pollution Discharge Elimination System (NPDES) permit limitations established by the USEPA.(1) The characteristics of the distribution about this limitation were obtained from data from a similar wastewater treatment facility on the same watershed treating approximately the same waste for the period 1985-1986. Phosphorus concentration data were used rather than loadings to achieve compatibility with phosphorus utilization by algae. That is, algae growth models are based upon concentration of substrate and are linear with respect to the actual component over a significant early range. This resulted in narrower distributions than could be achieved by loadings providing an added benefit in allowing the algal growth response to be maintained more readily in the linear range of the algal growth rate versus phosphorus concentration curve developed by Michaelis-Menten.(15) This allowed greater flexibility in manipulating the phosphorus delivered to the lake following discharge from the Fayetteville point source.

TABLE IV

ILLINOIS RIVER AND TRIBUTARIES
DRAINAGE BASIN DATA (12)

Stream Name & Loacation	Illinois River River Mile @ Confluence	Base Flow (cfs)	Stream Gauge Data Responsible Agency	Stream Gauge Data Period of Record	Historical Mean N:P Ratio	Drainage Area (sq. miles)
Clear Creek, Arkansas	132.8	12	C.O.E.	1985	46:1	84
Osage Creek, Arkansas	123.7	30	C.O.E.	1985	6:1	206
Flint Creek Ark. and Ok.	92.8	25	U.S.G.S.	1976-1985	10:1	170
Tahlequah Creek Oklahoma	52.5	5	C.O.E.	1985	4:1	14
Baron Fork Creek Ark. and Ok.	48.7	45	U.S.G.S.	1975-1985	25:1	307
Caney Creek, Oklahoma	39.2	14	C.O.E.	1985	3:1	97
Illinois River @ Headwaters of Lake Tenkiller Ferry	40.0	200	U.S.G.S.	1976-1985	15:1	1610

The Illinois River was initially modeled with the historic point source data and again with the Fayetteville waste added as additional point source to the Clear Creek tributary. Log normal distributions were determined for all nitrogen and phosphorus forms as well as five day biological oxygen demand (BOD_5), dissolved oxygen, temperature and pH. These parameters were input as variables in the water quality model. Distributions were used to augment routed upstream point and non-point phosphorus concentrations. Addition of the material to the routed concentration represents additional point and non-point source phosphorus contributed to the watershed from these intermediate locations. Kinetic, physical and hydraulic parameters were obtained from U.S.G.S., States of Arkansas and Oklahoma agency data and publications as well as QUAL2E-UNCAS default values. These values were input as normally distributed variables using QUAL2E-UNCAS default statistical variance data. QUAL2E-UNCAS repeatedly accessed individual input values from these distributions, completed individual simulations and accumulated these intermediate values. The Monte Carlo simulations were repeated until the 95% upper and lower confidence intervals reached constant levels. Figure 8 in Chapter II is an example of this method. A minimum of 2000 simulations were performed for all analyses.

The resultant distributions describing the historic low flow and that generated to include the additional Fayetteville point source were then each randomly accessed. These values were subtracted from each other with the difference being the low flow, steady-state contribution from the proposed point source from Fayetteville at Lake Tenkiller. This procedure was repeated until the entire phosphorus concentration distribution from Fayetteville was developed.

Using the previously described phosphorus concentration distribution at the Fayetteville plant and the phosphorus concentration distribution of treated Fayetteville effluent at Lake Tenkiller calculated from the distributions obtained from QUAL2E-UNCAS the channel loss of phosphorus per river mile was determined. The remaining phosphorus concentration at the lake was subtracted from the concentration at the plant and divided by the distance traveled. This loss per mile function data set was used in later simulations. Figure 7 in Chapter II displays the probability plots of these three distributions. In a similar fashion to the precision ensuring approaches previously described, the entire distribution was considered developed when the mean and the standard deviation of the generated distribution reached constant values. Figure 9 in Chapter II presents these results.

<u>Determination of Run of the River Loading.</u> In order to determine realistic eutrophication potential occurring in Lake Tenkiller the loading was calculated with the Illinois River flows in a dynamic rather than steady-state condition. The run of the river historical phosphorus load distribution was generated from the U.S.G.S. monthly phosphorus concentration monitoring data and from the mean daily inflow data

to Lake Tenkiller. The resultant distribution assumed no correlation between these input data sets. A second data set was prepared using the previously described loading condition and randomly adding the loading distribution for the Fayetteville point source at Lake Tenkiller to that derived from the U.S.G.S. data. The resulting data set was the historical loading with the addition of Fayetteville treated effluent. These two distributions were examined for their impact on eutrophication potential using a variety of graphical technique. One serving as the base condition and the other to be expected from the Fayetteville augmented conditions.

Determination of Point and Non-Point Source Loading Distributions. Additional work conducted in this research obtained the distributions for point and non-point source loadings from the States of Oklahoma and Arkansas. Point sources were taken to be from wastewater treatment plants which were all assumed to have constant flows. The total point source load at Lake Tenkiller was obtained by individually accessing each wastewater treatment plant's phosphorus concentration distribution and routing this concentration downstream using the previously described phosphorus channel loss function. The resulting concentrations were converted into loads and randomly added providing the total point source load at Lake Tenkiller. Table V provides a summary of the statistical parameters for phosphorus at Lake Tenkiller resulting from the various wastewater treatment plants.

The point source distribution was subsequently disaggre-

TABLE V

SUMMARY OF POINT SOURCE DATA AT THE
LAKE TENKILLER FERRY

Location City	Tributary Receiving Effluent	Plant Flow (MGD)	Phosphorous Loading Parameters (mg/l) Min.	Max.	Mean	Std. Dev.	95% UCL	95% LCL	Distance to Tenkiller (miles)	Distance Watts (miles)
Fayetteville Arkansas	Clear Creek	6	0.00	0.23	0.158	0.054	0.181	0.134	106	47
Rogers Arkansas	Osage Creek	3.5	0.00	11.05	3.829	2.810	5.031	2.627	95	37
Springdale Arkansas	Osage Creek	7	0.00	6.05	3.345	1.467	3.972	2.718	95	37
Siloam Springs Arkansas	Flint Creek	2.4	0.00	4.86	1.609	1.427	2.219	0.999	68	-
Tahlequah Oklahoma	Tahlequah Creek	1.0	0.00	6.58	4.632	1.128	5.110	4.150	20	-
Stillwell Oklahoma	Caney Creek	0.7	0.00	16.54	8.80	5.129	10.990	6.610	35	-

gated from the total historical load delivered at Lake Tenkiller with the Fayetteville additions. This resulted in the total non-point source loading to Lake Tenkiller. In a similar manner the wastewater treatment plants in the States of Oklahoma and Arkansas were individually examined to determine the point source contribution from each state.

In order to determine the non-point source loading from Oklahoma and Arkansas it was necessary to obtain the distribution of total loading from Arkansas. Using the U.S.G.S. water quality/discharge gauge closest to the state border, Watts, Oklahoma the total run of the river historic load was determined using distributions prepared from the monthly phosphorus concentration and the mean daily discharge. All loadings at this gauge were considered to have been generated by Arkansas sources. The total point source load at Watts was disaggregated from the total load resulting in the non-point source distribution. Randomly applying the channel phosphorus loss per mile distribution for the distance to Lake Tenkiller the Arkansas non-point source distribution to Lake Tenkiller was determined. This data set was subtracted from the total non-point source distribution resulting in the Oklahoma non-point source loading distribution. Table VIII in Chapter II provides a summary of the derived distributions and their uses in this study.

Phosphorus Removal Alternatives. Using the point and non-point source phosphorus loading distributions various phosphorus removal alternatives were examined to determine the effect on eutrophication potential. Figure 3 provides a flow chart showing the sequences used to complete these tasks. The alternatives simulated were the 70% removal of Oklahoma total load, 70% removal of Arkansas total load, 70% removal of Oklahoma or Arkansas non-point source loads, 25, 50, 70 and 90% removal of total combined loads. These percentages of removal were chosen arbitrarily without regard to economics or engineering feasibility.

Vollenweider Methods

The Vollenweider method and graph was used to convert the various phosphorus loads as well as lake properties into indicators of eutrophication. This method compared the effect of the addition of the point source loads from Fayetteville as well as the various removal options for phosphorus. The lake operations and hydraulic data in conjunction with river loading conditions were used to define eutrophication loading potential (Lp) which is the value of the annual loading (grams/year) contributed to the surface area of the lake (m^2) (g/m^2/year). Table XI in Appendix A shows the relationship between pool elevation and surface area and storage volume and Figure 27 is a plot of this relationship.(10) The hydraulic parameter (Qs) is the mean depth (meters) divided by the hydraulic retention time (years) (meters/year). Figure 5 in Chapter II is a sample of the Vollenweider graph. Similarly, there are samples of Vollenweider calculations in Appendix A. The converted

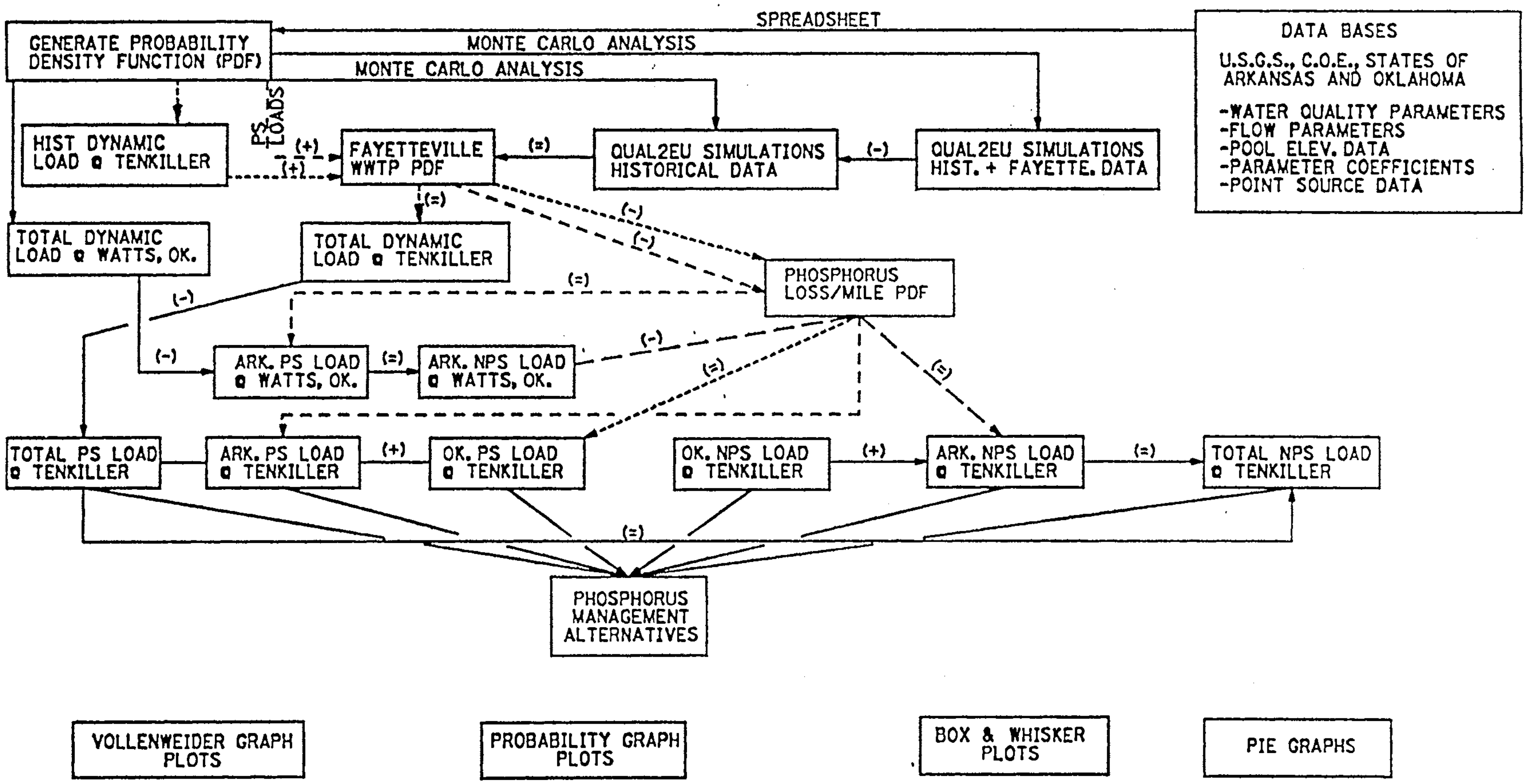


Figure 3. Logic Sequence Illinois River Analysis

values can fall into three potential areas developed by Vollenweider, the eutrophic, oligotrophic and the mesotrophic zones.(16) The phosphorus loads selected from previously developed distributions and mean and monthly lake inflows were projected on an annual basis. There was no correlation assumed between distributions. The distributions were plotted on the Vollenweider graph. These values represented a source of eutrophication potentials for given phosphorus loading and management options.

As presented, the Vollenweider method was not capable of evaluating probability of eutrophication occurrence. Each plotted point potentially has a variety of background probabilities associated with its component parts. An alternative parameter, called the Vollenweider Number for this effort, was used to approximate eutrophication potential. The Vollenweider Number, the product of the Qs times the Lp, was used to approximate eutrophication potential. Standard probability techniques were then used to define a Vollenweider like distribution.

Additional Graphical Techniques

Probability graph plots, "box and whisker" plots (17), and pie charts were also used in this study. "Box and whisker" plots compare various specific statistical values of distributions and selected phosphorus management alternatives. The "box" contains 25%, median and 75% values. The 95% upper and lower confidence limits about the mean are shown with brackets. The ends of the whiskers indicate the minimum and maximum values. An overlap of the confidence intervals were used as a comparison of statistical similarity among the various distributions.

Pie graphs were used to display effects of the selected phosphorus removal alternatives and the effect of the addition of Fayetteville treated effluent. These pie graphs displayed a comparison of the effectiveness using the run of the river historical loading distribution with the Fayetteville point source added as the base case for comparison.

Results

Illinois River Water Quality Data

The initial phase of the study necessitated the manipulation of historical data for the QUAL2E-UNCAS water quality model. All homogeneous reaches used for analysis produced log normal distributions. Figure 6 in Chapter II is the phosphorus probability for the four mainstem U.S.G.S. water quality gauges and Table IX in Chapter II is a statistical summary for these gauges. These plots were typical of all variable data used in the water quality model.

Eutrophication Potential Analyses

Fayetteville Treated Effluent Distributions. The Monte Carlo simulation techniques generated a probablistic output for the historical point source data with and without the Fayetteville treated effluent added. Table X in Chapter II provides a summary of the statistical output and Figure 7 in Chapter II provides a probability plot of the randomly generated Fayetteville effluent distribution as well as the distribution of phosphorus concentration at the plant and the phosphorus channel loss per mile data set.

Run of the River Loading Distributions. The total run of the river loading distributions for historical data and for historical data with the addition of treated Fayetteville effluent to Lake Tenkiller were generated and converted into Vollenweider parameters as described previously. Figure 11 in Chapter II is the probability plot for the Vollenweider Number and the Vollenweider Loading (Lp) Values distributions for the two dynamic loading distributions. Figure 12 is the various graphical comparisons of these two distributions to determine the overall effect on eutrophication potential from Fayetteville effluent.

Point and Non-Point Source Loading Distributions. Additional work conducted in this study included the derivation of the point and non-point source loadings from the States of Oklahoma and Arkansas. Figure 14 in Chapter II is the "box and whisker" plots of the statistical parameters of the generated point and non-point source loading distributions which are summarized in Table VI.

Phosphorus Removal Alternatives. Figures 15 through 26 in Chapter II examine graphically the effects of selected phosphorus removal alternatives previously described. Figures 15 and 16 are the probability plots for the Vollenweider

TABLE VI

POINT AND NON-POINT SOURCE LOADING
SUMMARY AT LAKE TENKILLER FERRY
(pounds per day)

Stat. Data	Hist. Load	Hist.+Fayett. Load	Tot. PS	Tot. NPS	OK. PS	OK.NPS	ARK. PS	ARK. NPS
				Loading Conditions				
Mean	1180.91	1181.67	387.41	684.81	55.04	415.40	165.92	189.05S
Std. Dev.	2282.63	2282.45	128.76	1840.95	27.49	231.71	135.12	840.02
Minimum	1	1	0	1	0	1	0	0
Maximum	23000	23024	1215	21800	355	3600	860	18200
25% Value	174	174	292	261	33	225	11	66
75% Value	1190	1190	460	780	79	610	240	535
95% LCL	864.55	865.34	405.26	429.67	51.28	383.29	147.19	72.63
95% UCL	1497.27	1498.00	369.56	939.95	58.90	447.51	184.65	305.47

Loading (Lp) Values and the Vollenweider Number, respectively for the selected phosphorus removal alternatives. Figures 17 and 18 are the "box and whisker" plots of the distribution shown in Figures 15 and 16. Figures 19 through 24 are the selected removal alternative distributions plotted on the Vollenweider graph. Figures 25 and 26 are the pie graphs for the same alternatives shown on Figures 19 through 24. The pie graphs show the overall effectiveness of each of the removal alternatives by showing the decrease in the percentage of points in the eutrophic zone.

Discussion

A summary of the overall results of this effort are shown in Table XI in Chapter II. The results indicate that Fayetteville treated effluent has minimal impact on eutrophication potential in Lake Tenkiller. This is shown by the graphical comparisons in Figure 12 and 13. In Figure 12 the 95% upper and lower confidence limits in the "box and whisker" plots overlap, therefore, the distributions are statistically similar. There is a slight increase in eutrophic points displayed in the pie graphs however, which appears due to the sensitivity of the Vollenweider graph to increases in phosphorus loading. The Vollenweider graph shows that both distributions overlap and there is virtually no upward shift in the distribution. In Figure 13 the probability plot of these two distributions are indistinguishable from each other. The majority of the phosphorus discharged from the plant was removed by natural processes in the river as it traveled to Lake Tenkiller. The Vollenweider method seems to indicate Lake Tenkiller currently has a significant eutrophication problem. The main factor effecting this pollution appears to be non-point source phosphorus. This is illustrated in Figures 13 and 14. This non-point source loading appears to be almost equally supplied by both the States of Oklahoma and Arkansas as shown in Figure 12 and by the "box and whisker" plots in Figure 14. Each state seems to have sufficient loading capacities to continue the eutrophication process of the lake if the other states' load was reduced. This explains why individual state removal efforts examined in this research had only a minor effect on lake eutrophication reduction. Only total phosphorus removal options seem to have a significant lowering of the eutrophication potential. Figures 19 through 24 show the downward shift of the distribution into the oligotrophic zone for high total phosphorus removals but very little shift for individual state removal alternatives.

Conclusions

The stochastic method of determining phosphorus loading distributions utilizing historical water quality, discharge and lake hydraulic and operational data employed in this research:

1. Provided a simpler, more workable and less time consuming alternative to analyses of eutrophication than was

possible with dynamic wave and/or complex watershed models.

2. Due to the fact that eutrophication normally involves a broad time horizon this method can be used in tandem with steady-state, low flow, time independent models to ascertain the potential impact of various point and non-point source phosphorus loads.

3. Allows the analysis of an entire distribution of loadings instead of means or extremes which is essential in defining appropriate range of watershed management alternatives.

The results of the various derived phosphorus loading distributions and representations of these distributions by the various graphical techniques used in this study indicate that:

1. Lake Tenkiller Ferry appears to have a significant eutrophication problem due to non-point source phosphorus loading.

2. Treated wastewater effluent from Fayetteville, Arkansas seems to have a minimal effect on increasing the eutrophication potential in Lake Tenkiller.

3. Oklahoma and Arkansas appear to contribute equal amounts of phosphorus load to Lake Tenkiller and the Illinois River.

4. Individual state removal of phosphorus seem to have some beneficial impact on reducing phosphorus load levels. However, the removal of the large percentages of total load is necessary to bring phosphorus pollution under control.

CHAPTER II

A STOCHASTIC EVALUATION OF PHOSPHORUS CONTROL ALTERNATIVES ON EUTROPHICATION POTENTIALS IN A MULTI-PURPOSE RESERVOIR

Introduction

In late 1985, the City of Fayetteville, Arkansas was granted authorization by the United States Environmental Protection Agency (USEPA) to discharge treated effluent into Mud Creek, a tributary of Clear Creek which flows into the Illinois River approximately 90 miles above the headwaters of Lake Tenkiller.(1) Figure 4 presents a schematic of these locations as well as the remainder of the Illinois River Basin. There was immediate concern expressed by representatives of the State of Oklahoma and other interested parties within the state that this additional waste load would cause water quality deterioration in the Illinois River and Lake Tenkiller. This watershed is highly valued for its scenic, recreational, agricultural and power generation capabilities. Table VII provides additional data on the Illinois River basin and Lake Tenkiller.

Much of this concern centered upon increasing eutrophication in the reservoir where seasonal oxygen depletion as well as increased phytoplankton counts have been recorded in

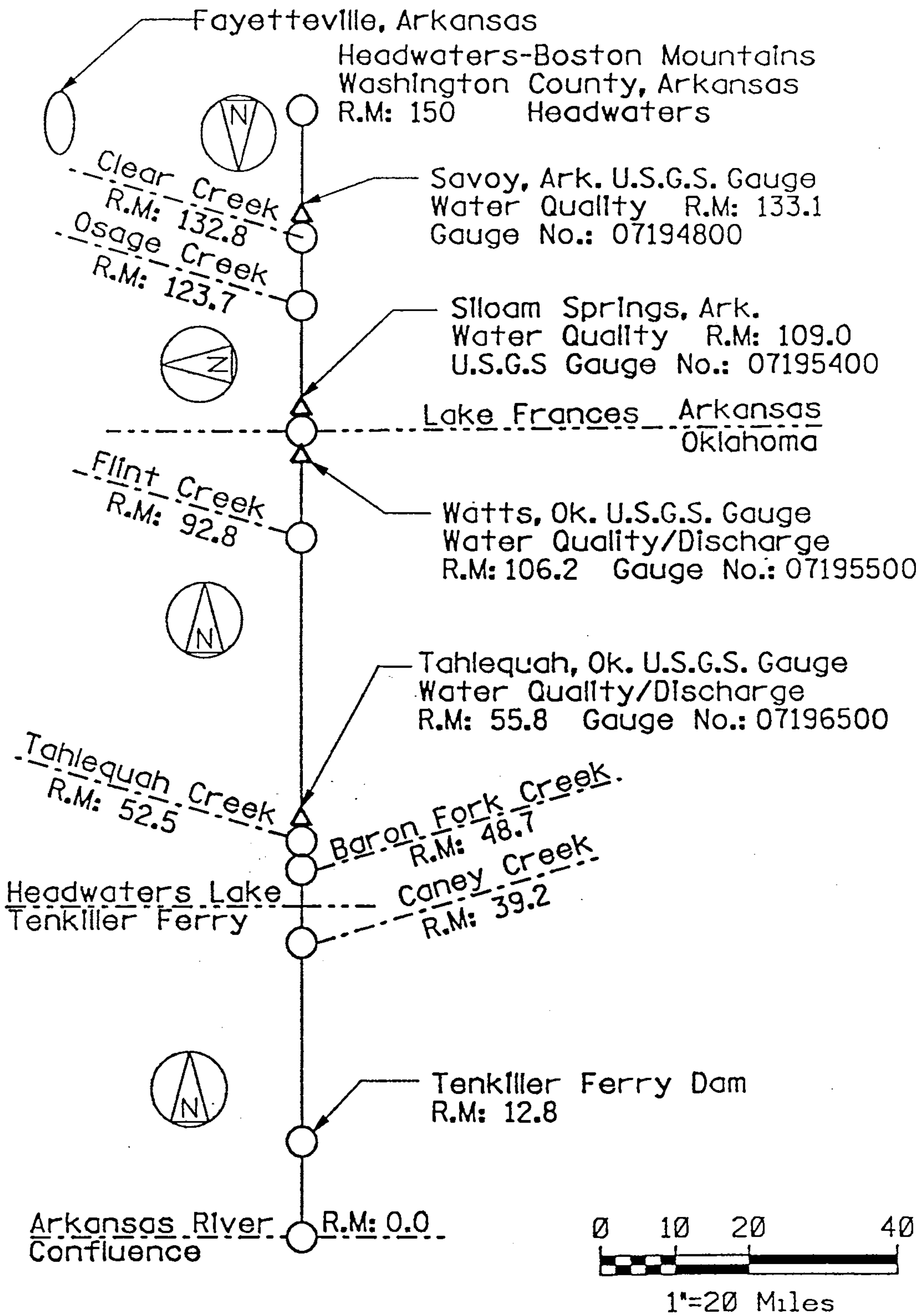


Figure 4. Illinois River Schematic

TABLE VII

SUMMARY OF PERTINENT OPERATIONAL VARIABLES DESCRIBING LAKE TENKILLER FERRY, OKLAHOMA (10)

Subject	Data
Drainage Area	1,660 square miles
Top of Power Pool Elev.	632.0
Storage Capacity @ Power Pool Elev.	654,100 ac-ft.
Surface Area @ Power Pool Elev.	12,900 acres
Top of Flood Control Pool Elev.	667.0
Storage @ Top of Flood Control Pool	1,230,800 ac-ft.
Surface Area @ Top of Flood Pool	20,800 acres

recent years.(2)

Historically, accelerated rates of eutrophication in lakes have been attributed to increases in the amounts of macro and trace nutrients in the upstream watershed. If left unchecked, the abundance of nutrients (carbon-C, nitrogen-N, phosphorus-P and others) often leads to undesirable water quality; increased turbidity, reduced dissolved oxygen, taste and odor problems, algal blooms, clogged raw water intakes, fish kills and ultimately increased sedimentation until the basin fills and the lake has no further utility.(3) Although a natural process, eutrophication has been shown to increase dramatically in the presence of uncontrolled point and non-point source discharges of macro and trace nutrients. Owing to the ubiquity of certain common elements as well as to the stoichiometric requirements of offending algal species, the generally accepted control approach has been to remove either nitrogen or phosphorus from waters draining into lakes and reservoirs. If the ratio of nitrogen to phosphorus (N:P) in the lake or reservoir of concern is less than 5, algal growth is generally considered to be nitrogen limited. If this ratio is between 5 and 10, eutrophication may be influenced by either or both nutrients while N:P in excess of 10 is generally indicative of phosphorus limitations.(4)

Monthly water quality data from 1976 through 1985 for the Tahlequah, Oklahoma water quality gauge on the Illinois River, which is directly above the confluence with Lake Tenkiller, has a N:P ratio of 15:1. Based on these and related main stem and pool data Lake Tenkiller was considered phosphorus limited and additional analysis of eutrophication potentials within the reservoir focused on phosphorus presence and removals. The research reported herein developed and applied an analysis technique to determine the probability of increased eutrophication potential at Lake Tenkiller initially from point source discharge from Fayetteville and subsequently from various levels of phosphorus discharge within the Illinois River watershed. The techniques employed in this analysis utilized a stochastically based steady-state modeling effort in tandem with long term phosphorus monitoring data. A more complete description of this effort follows.

Model Selection

Even though the principal concern of this effort was to evaluate the probability of eutrophication in Lake Tenkiller given alternative phosphorus management options, the analysis initially focused on the upstream watershed. That is, a determination of the loads delivered by the Illinois River to the reservoir was the primary concern of the effort. These loads were projected by a combination of computer modeling and historical data analysis. Reservoir pool capacities and hydraulic detention times were then used to determine the impact of these projected phosphorus loads on eutrophication potential in Lake Tenkiller.

The types of methods considered for use in this effort were; the dynamic wave, and steady state or static simulation models. Dynamic wave or transient flow models allow for changes over time and time-varying interactions while static approaches address time-independent processes. Available models can be further divided into total watershed codes or those that address channel processes only. Examples of dynamic watershed approaches include HEC-1(18), TR-20(19), HSPF(20) and others, while HEC-2(21) and CE-QUAL-R1V1(22) are used for time varying channel flow and water quality simulations. QUAL2E-UNCAS(23) is perhaps the most commonly employed steady state model used to simulate pollutant transport in channels and ultimately to a receiving body. Each of these approaches affords significant benefits as well as severe limitations when applied to a basin as large and complex as the Illinois River Watershed. HEC-1, TR-20 and HEC-2 do not include water quality processes within their codes and were eliminated from further consideration, while HSPF is a complex watershed code that simulates upland as well as channel processes. It was judged inappropriate to this effort because of its extensive data requirements and its focus upon land based rather than channel and reservoir features. The amount of effort required to calibrate this code to the 1600 square mile Illinois River basin was considered infeasible given the principal objectives of the effort to ultimately identify the probability of eutrophication in Lake Tenkiller given a wide variety of possible phosphorus control alternatives.

The CE-QUAL-R1V1 code was considered more appropriate to this task. It was capable of simulating pollutant transport within channels affected by transient flow conditions. This becomes necessary if real-time phosphorus delivery through the river to the reservoir is required. Non-point, runoff driven phosphorus would be mobilized and transported under these type of flow regimes. The model was not universally available however, and required such relatively extensive and unavailable input data such as channel cross sections and other hydraulic features that is was considered inappropriate for this effort. Further, without modification this model as well as the previously described codes were unable to define the probability of a given phosphorus load or eutrophication event. That is they are deterministic rather than stochastic codes. An alternative approach was sought.

While non-point source pollution is storm and runoff driven, eutrophication having a much broader time horizon, does not require real-time loads. A longer time step is acceptable. That is, while the capability of accurately simulating non-point source phosphorus distribution to the system is critical, the greater complexity associated with the simulation of time dependent hydraulics is not a critical factor in eutrophication analysis. A method is presented which utilizes existing, long-term water quality monitoring data in concert with a steady state channel model to develop probability density functions which were subsequently accessed to define a level of probability of occurrence for a given phosphorus load. These low flow events were manipulated to present only the projected Fayetteville phosphorus concentration delivered to the reservoir. As these are point source contributors these loads can be readily addressed by this type of steady state analysis. This method used static or steady-state modeling to define the phosphorus load associated with the low flow events and subsequently coupled these determinations with the historical data base which included flood driven phosphorus from sources throughout the basin to develop the entire distribution of phosphorus delivered to the reservoir with the Fayetteville treated effluent included.

Experimental

Methods Analysis

The model selected for this effort was the USEPA's QUAL2E-UNCAS which is a stochastic, steady-state hydraulic, dynamic nutrient water quality code. QUAL2E-UNCAS allows the user to perform uncertainty analysis on the steady state water quality simulations. With this capability the user can assess the effect of model sensitivities and of uncertain input data on the model forecasts. One of the risk assessing features of this model is the Monte Carlo simulations technique. Monte Carlo simulations randomly sample input variables from predetermined probability distribution as repeated inputs to a deterministic coding to eventually produce a probablistic output in the form of frequency and cumulative frequency distributions and summary statistics at user specified locations in the system.

Eutrophication Potential Analysis

Determination of Fayetteville Treated Effluent Distribution. The QUAL2E-UNCAS model was used to determine the phosphorus distributions in the Illinois River under point source discharge conditions. The Fayetteville maximum phosphorus concentration used in this effort was at the National Pollution Discharge Elimination System (NPDES) permit limitations established by the USEPA.(1) The characteristics of the distribution about this limitation were obtained from data from a similar wastewater treatment facility on the same watershed treating approximately the same waste for the period 1985-1986. Phosphorus concentration data were used rather than loadings to achieve compatibility with phosphorus utilization by algae. That is, algae growth models are based upon concentration of substrate and are linear with respect to the actual component over a significant early range. This resulted in narrower distributions than could be achieved by loadings providing an added benefit in allowing the algal growth response to be maintained more readily in the linear range of the algal growth rate versus phosphorus concentration curve developed by Michaelis-Menten.(15) This allowed greater flexibility in manipulating the phosphorus delivered to the lake following discharge from the Fayetteville point source.

The river was initially modeled with the historical point source data and again with the Fayetteville waste added. In all cases, the tributaries were treated as point source loads at the point of confluence with the Illinois River mainstem. Concentration distributions without correlation were developed for all nitrogen and phosphorus forms (nitrate, ammonia, nitrite, total Kjeldahl N, phosphate and p-total) as well as five day biological oxygen demand (BOD_5), dissolved oxygen, water temperature and pH. These values were entered as log normal, variable distributions with statistical variances determined by historical data. The kinetic, hydraulic and physical coefficients were obtained from USGS data and existing studies as well as QUAL2E-UNCAS supplied default values.(11-14) These values were input as variable, normal distributions using QUAL2E-UNCAS default values for statistical variances.(23) The QUAL2E-UNCAS randomly and repeatedly accessed individual input values from these distributions, completed individual simulations and tallied these intermediate findings. Distributions of these same constituents were used to augment routed upstream point and non-point phosphorus concentrations at intermediate gauging stations along the mainstem. Addition of the material to the routed concentration represents additional point and non-point source phosphorus contributed to the watershed from these intermediate locations. The Fayetteville effluent was simply added as an increase in the distribution of the point source describing the Clear Creek tributary. Two thousand Monte Carlo simulations were used for all analyses. This was considered to be an adequate number given previous investigations but was further verified by determining the upper and lower 95% confidence limits for the simulated mean and standard deviation values as a function of the number of simulations performed.(23) Simulations were repeated until the interval between the upper and lower 95% confidence intervals reached a constant value.

Using the previously described phosphorus concentration distribution at the Fayetteville plant and the phosphorus concentration distribution of treated Fayetteville effluent at Lake Tenkiller calculated from the distributions obtained from QUAL2E-UNCAS the channel loss of phosphorus per river mile was determined. The remaining phosphorus concentration at the lake was subtracted from the concentration at the plant and divided by the distance traveled. This loss per mile function data set was used in later simulations. Figure 7 displays the probability plots of these three data sets.

In a similar fashion to the precision ensuring approaches previously described, the entire distribution was considered developed when the mean and the standard deviation of the generated distribution reached constant values. Figure 9 presents these results.

The resultant distributions describing the historic low flow condition and that generated to include the additional phosphorus from Fayetteville were then each randomly accessed. These individual contributions were then subtracted from each other. The difference equaled the low flow steady-state contribution resulting from the proposed Fayetteville discharge at Lake Tenkiller. This was done repeatedly until the entire distribution of phosphorus as concentration from Fayetteville delivered to Lake Tenkiller was developed.

Determination of the Run of the River Loading Distribution. In order to determine realistic eutrophication potential occurring in Lake Tenkiller the loading must be obtained with the Illinois River flows in a dynamic rather than a steady-state condition. The phosphorus load distribution for the historic base case was generated from the monthly USGS phosphorus concentration distribution and one prepared for mean daily inflow to the reservoir. These distributions were randomly accessed assuming no existing correlation. That is, any phosphorus concentration could occur with any flow. This load was subsequently used to determine eutrophication potentials in the reservoir. This distribution was then randomly accessed and added to a similar data set derived from the distribution of phosphorus from the Fayetteville treatment plant as delivered to Lake Tenkiller. This gave the entire loading function of the historical point and non-point source augmented by the Fayetteville contribution.

Determination of Point and Non-Point Source Loading Distributions. Additional work conducted in this research obtained the distributions for point and non-point source loadings from the States of Oklahoma and Arkansas. Point sources were assumed to be totally from wastewater treatment plants which were all assumed to have constant flows. Non-point sources were runoff oriented. The total point source load at Lake Tenkiller was obtained by individually accessing each wastewater treatment plant's phosphorus concentration distribution and routing this concentration downstream using the previously described phosphorus channel loss per mile distribution. The resulting concentrations were converted into loads and randomly summed providing the total point source load data set at Lake Tenkiller. The distribution was disaggregated from the total historical load delivered with the Fayetteville additions. This resulted in the total non-point source loading to Lake Tenkiller. In a similar manner the wastewater treatment plants in the States of Oklahoma and Arkansas were individually examined to determine the point source contribution from each state.

In order to determine the non-point source loading from Oklahoma and Arkansas it was necessary to obtain the distribution of total loading from Arkansas. Using the U.S.G.S.

water quality/discharge gauge closest to the state border, Watts, Oklahoma the total run of the river historic load was determined using distributions prepared from the monthly phosphorus concentration and the mean daily discharge. All loadings at this gauge were considered to have been generated by Arkansas sources. The total point source load at Watts was disaggregated from the total load resulting in the non-point source distribution. Applying the channel phosphorus loss per mile distribution for the distance to Lake Tenkiller the Arkansas non-point source distribution to Lake Tenkiller was determined. This data set was subtracted from the total non-point source distribution resulting in the Oklahoma non-point source loading distribution.

Phosphorus Removal Alternatives. These various point and non-point source distributions were then manipulated to determine the effects of various phosphorus removal alternatives on the loads to Lake Tenkiller. The options simulated were the 70% removal of Oklahoma total load, 70% removal of Arkansas total load, 70% removal of Oklahoma or Arkansas non-point source loads, 25, 50, 70 and 90% removal of total combined loads. These percentages of removal were chosen arbitrarily without regard to economics or engineering feasibility. Methods of determining eutrophication potential from loading and lake data are described below. Table VIII is a summary of the sources and uses for the developed distributions.

TABLE VIII

SUMMARY OF DEVELOPED DISTRIBUTIONS

No.	Distribution	Distribution Source	Purpose
(1)	Phosphorus Conc.	-U.S.G.S. -C.O.E.	-Use in water quality model. -Determination of run of the river historical loading.
(2)	Mean Daily Discharge	-U.S.G.S.	-Determination of run of the river historical loading.
(3)	Mean Monthly Lake Inflow	-C.O.E.	-Vollenweider calculations.
(4)	Mean Monthly Lake Pool Elevation	-C.O.E.	-Vollenweider calculations.
(5)	Low Flow, Steady-State Phosphorus Conc. @ Lake Tenkiller	-QUAL2E-UNCAS	-Determination of low flow phosphorus conc. from treated Fayetteville effluent.
(6)	Low Flow, Steady-State Phosphorus Conc. w/ Treated Fayetteville Effluent @ Lake Tenk.	-QUAL2E-UNCAS	-Determination of low flow phosphorus conc. from treated Fayetteville effluent.
(7)	Fayetteville Treated Effluent @ Lake Tenk.	- (6) (-)* (5)	-Determination of effect of Fayetteville on lake eutrophication. -Determination of point and non-point source loading distribution @ Lake Tenkiller.

TABLE VIII (Continued)

No.	Distribution	Distribution Source	Purpose
(8)	Historical Run of the River Loading	- (1) (X) (2)	-Determine existing eutrophication status -Base case loading distribution.
(9)	Historic Run of the River Loading w/ Fayetteville Effluent	- (7) (+) (8)	-Determine effect of Fayetteville point source on eutrophication. -Base case for point and non-point source loading distribution determination.
(10)	Phosphorus Loss Distribution	-Fayetteville WWTP P-total dist. @ plant (-) (7)	-Obtaining point and non-point source loading distributions @ Tenkiller.
(11)	Oklahoma and Arkansas Point Source Distrib. Total PS Distribution	- Agency Data on WWTP Added (-) (10)	-Determination of loading rates to Lake Tenkiller. -State contributions of point source. -Obtain total NPS loading distribution.
(12)	Total NPS Loading @ Lake Tenkiller	-(9) (-) (12)	-Determination of loading rates to Lake Tenkiller. -Determine individual state NPS loading distributions.
(13)	Total Run of the River Historical Loading @ Watts, Oklahoma	-(1) (X) (2)	-Determine total Arkansas loading. -Determine Arkansas NPS loading @ Lake Tenkiller.
(14)	Total Point Source Load @ Watts, Ok.	-Agency WWTP Data (-) (10)	-Total Arkansas point source load at state border.

TABLE VIII (Continued)

No.	Distribution	Distribution Source	Purpose
(15)	Total NPS Loading @ Watts, Oklahoma	-(13) (-) (14)	-Total Arkansas NPS load at the state border.
(16)	Total Arkansas NPS Load @ Lake Tenkiller	-(15) (-) (10)	-Total Arkansas NPS loading distribution @ Lake Tenkiller. -Phosphorus removal alternatives.
(17)	Total Oklahoma NPS Load @ Lake Tenkiller	-(12) (-) (16)	-Total Oklahoma NPS loading distribution @ Lake Tenkiller. -Phosphorus removal alternatives.
(18)	Phosphorus Removal Alternatives	-(16) (X) (70%) -(17) (X) (70%) -(17 + 11) (X) (70%)(Ok.& Ark.) -(9) (X) (25,50, 70 and 90%)	-Effect of various removal options on reduction in lake eutrophication. -Vollenweider calculations.

*(+,-,X) refers to randomly accessed distributions involved in arithmetic manipulations.

Vollenweider Methods

The Vollenweider method and graph was selected to convert the phosphorus loads to indicators of eutrophication potential. This method was used to compare the effects of the addition of the Fayetteville treated effluent as well as those resulting from various phosphorus removal alternatives which could be applied throughout the watershed. In this manner the effects of various phosphorus management alternatives could be evaluated simultaneously. This approach used lake hydraulics and river loading conditions to define eutrophication potential by plotting the annual phosphorus load (Lp) delivered to the reservoir ($g/m^2/yr.$) versus a hydraulic parameter (Qs) which is the mean reservoir depth divided by the hydraulic retention time (m/yr.). Figure 5 presents an example of this graph which was developed by Vollenweider after analysis of phosphorus loading rates to lakes in Europe.(16) If the combination of phosphorus loading and lake hydraulics produced a value in excess of the dividing line developed by Vollenweider the lake was considered to be eutrophic. Similarly two other regions were developed: the oligotrophic meaning clean and the mesotrophic indicating a mean response. Randomly selected phosphorus loads and lake hydraulic values were selected from the distributions previously developed. The hydraulic value in this effort was the Vollenweider parameter, Qs. Distributions of monthly reservoir pool elevations and mean daily inflows were generated. Following random access, without correlation, these values

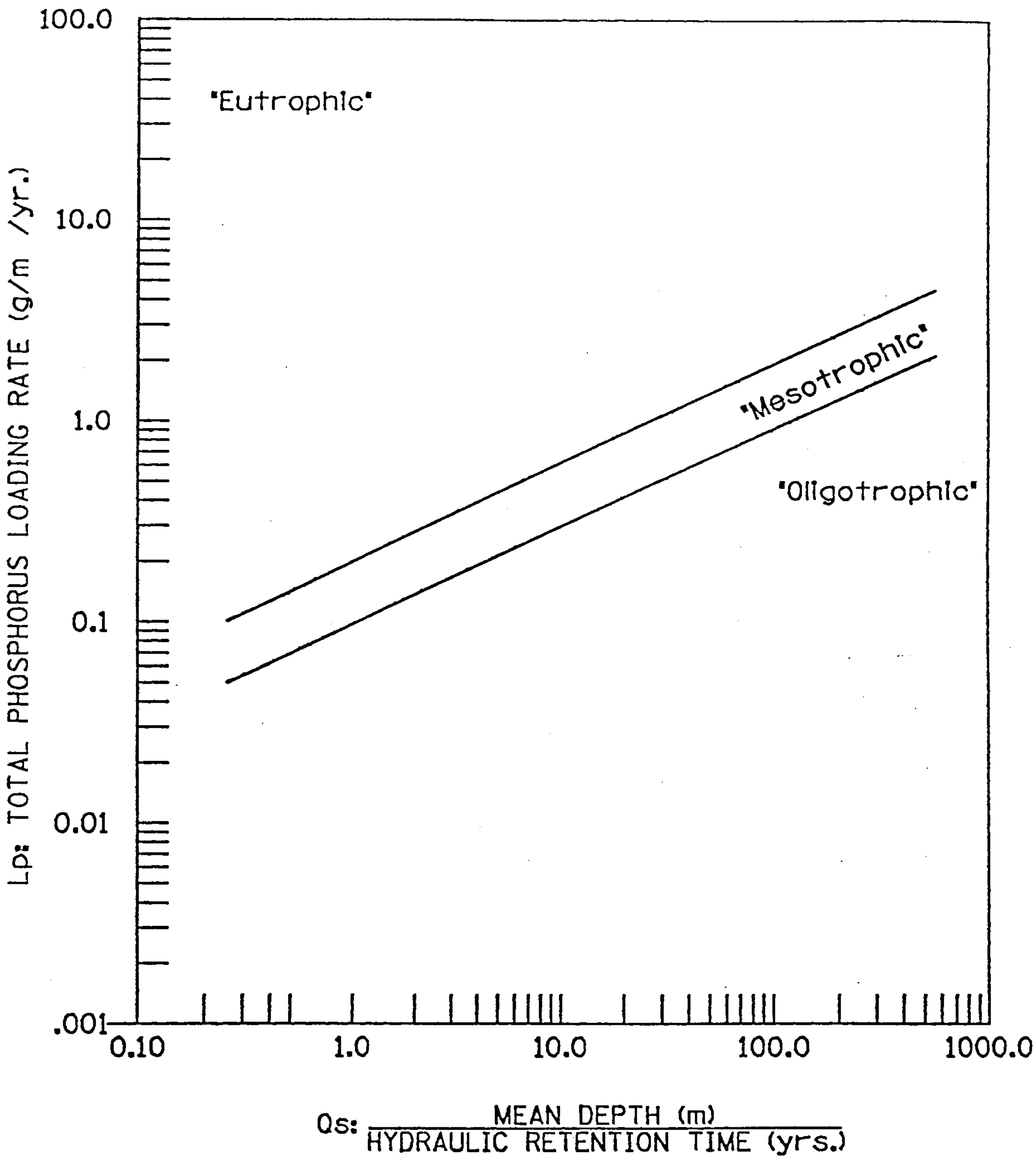


Figure 5. Sample Vollenweider Graph

were used to subsequently calculate the hydraulic detention time and the depth of the reservoir. A rating curve of pool elevation versus lake area and storage volume was developed for this purpose from COE data.(10) Sampling from these distributions continued until the values for the mean and the standard deviation of the simulated distribution reached a constant value to ensure adequate sampling precision. These points were then plotted on the Vollenweider scales, representing the eutrophication potential which could be expected for a given phosphorus management alternative.

Unfortunately, because of its basic structure, the Vollenweider graph does not lend itself to probability evaluations. Each plotted point potentially has a variety of background probabilities associated with its component parts. The product of the independently accessed values of Qs times the Lp was used as a first approximation of this property. Subsequently called the Vollenweider number, it was utilized in standard probability techniques to indicate the range of eutrophication potentials.

Additional Graphical Techniques

In addition to the Vollenweider graphs and the probability figures, "box and whisker" plots (17) and pie charts were used in this effort. The "box and whisker" plots represent the distributions of the historic loadings, the historic loadings with the addition of Fayetteville treated effluent, the various point and non-point source loadings and loadings expected after various selected phosphorus management alternatives were employed. The 25%, median and 75% values were used to construct the box while the extremes of the simulated data were presented by the whiskers. In addition the 95% upper and lower confidence intervals about the mean were displayed with brackets. The overlapping of upper and lower confidence intervals were used as a comparison of statistical similarity among the various distributions. That is, if the confidence intervals of the alternative distribution overlapped they could be said to be statistically similar. The pie graphs were used to display the effects of the selected phosphorus removal alternatives as well as the effects of the Fayetteville treated effluent addition to the existing historical loading. These graphs present the various percentages of points from the completed distributions falling in the three Vollenweider zones (eutrophic, mesotrophic and oligotrophic). These pie graphs provide a simple comparison of the effectiveness among the various management alternatives examined in this effort.

Results

Illinois River Water Quality Data

The initial phase of the study necessitated the manipulation of the chemical data for use in the water quality model. The distributions of these data were log normal for all reaches used in this analysis. Figure 6 presents the phosphorus distributions, which were typical of all distributions, for the four mainstem U.S.G.S. water quality gauges on the Illinois River. Table IX is a statistical summary for phosphorus at these four gauges. Baseflow, dissolved oxygen, pH, water temperature, nutrient forms (N, P) and five day biological oxygen demand were input as stochastic PDFs.

Eutrophication Potential Analyses

Fayetteville Treated Effluent Distribution. The Monte Carlo simulations produced a probablistic output for the historical point source conditions and subsequently a second distribution for the historical data with the addition of the Fayetteville treated effluent. Table X is a statistical summary of the phosphorus concentration data derived in these initial efforts. Using the previously described procedure, the PDF for the combined Fayetteville effluent as well as the historical phosphorus concentration at Lake Tenkiller was determined. Figure 7 presents the probability plots of the phosphorus concentration distributions for Fayetteville at the plant and what remains at Lake Tenkiller subsequent to the water quality modeling simulations. This figure also displays the phosphorus channel loss function which was used to disaggregate the various point and non-point source loading distributions from the historical loading data set.

Run of the River Loading Distributions. The historical mean daily inflow and phosphorus concentration distributions were used to obtain the total run of the river

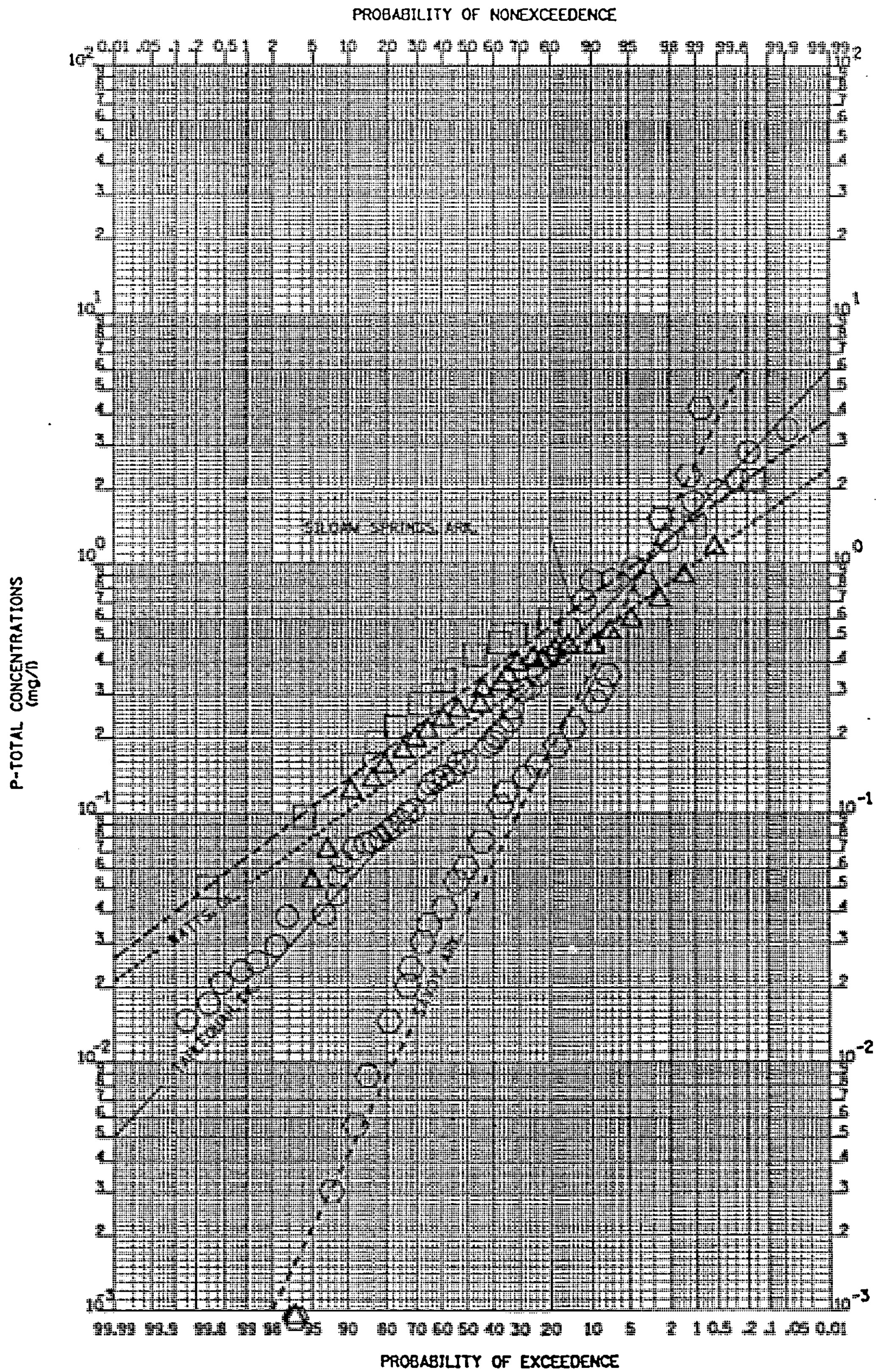


Figure 6. P-Total Distributions @ U.S.G.S. Water Quality Gauges on the Mainstem of the Illinois River

TABLE IX

SUMMARY OF STATISTICAL DATA ON PHOSPHORUS CONCENTRATION DISTRIBUTIONS ON FOUR ILLINOIS RIVER MAINSTEM U.S.G.S. WATER QUALITY GAUGES

	Water Quality Gauges (mg/l)			
Statistical Parameter	Savoy, Ark.	Siloam Springs Ark.	Watts, Ok.	Tahlequah, Ok.
Mean	0.106	0.297	0.248	0.184
Std. Dev.	0.242	0.157	0.131	0.303
Min.	0.010	0.070	0.005	0.005
Max.	1.700	0.740	0.830	2.430
95% UCL	0.158	0.330	0.269	0.259
95% LCL	0.054	0.264	0.227	0.109
Period of Record	1974-1987	1975-1981	1970-1985	1976-1985

TABLE X

STATISTICAL OUTPUT SUMMARY OF QUAL2E-UNCAS SIMULATIONS AT LAKE TENKILLER FERRY FOR P-TOTAL CONCENTRATIONS (mg/l)

Statistical Parameters	Historical Data Simulations	Historical + Fayetteville Simulations
Base Mean	0.037	0.063
Simulated Mean	0.037	0.063
Bias	0.000	-0.001
Minimum	0.003	0.005
Maximum	0.352	0.487
Range	0.349	0.482
Standard Deviation	0.030	0.047
Coefficient of Variation	0.807	0.758
Skew Coefficient	4.195	3.545

loading to Lake Tenkiller. The Fayetteville treated effluent PDF was combined with the historic loading distribution to obtain the anticipated run of the river loading to Lake Tenkiller and the run of the river loading to Lake Tenkiller

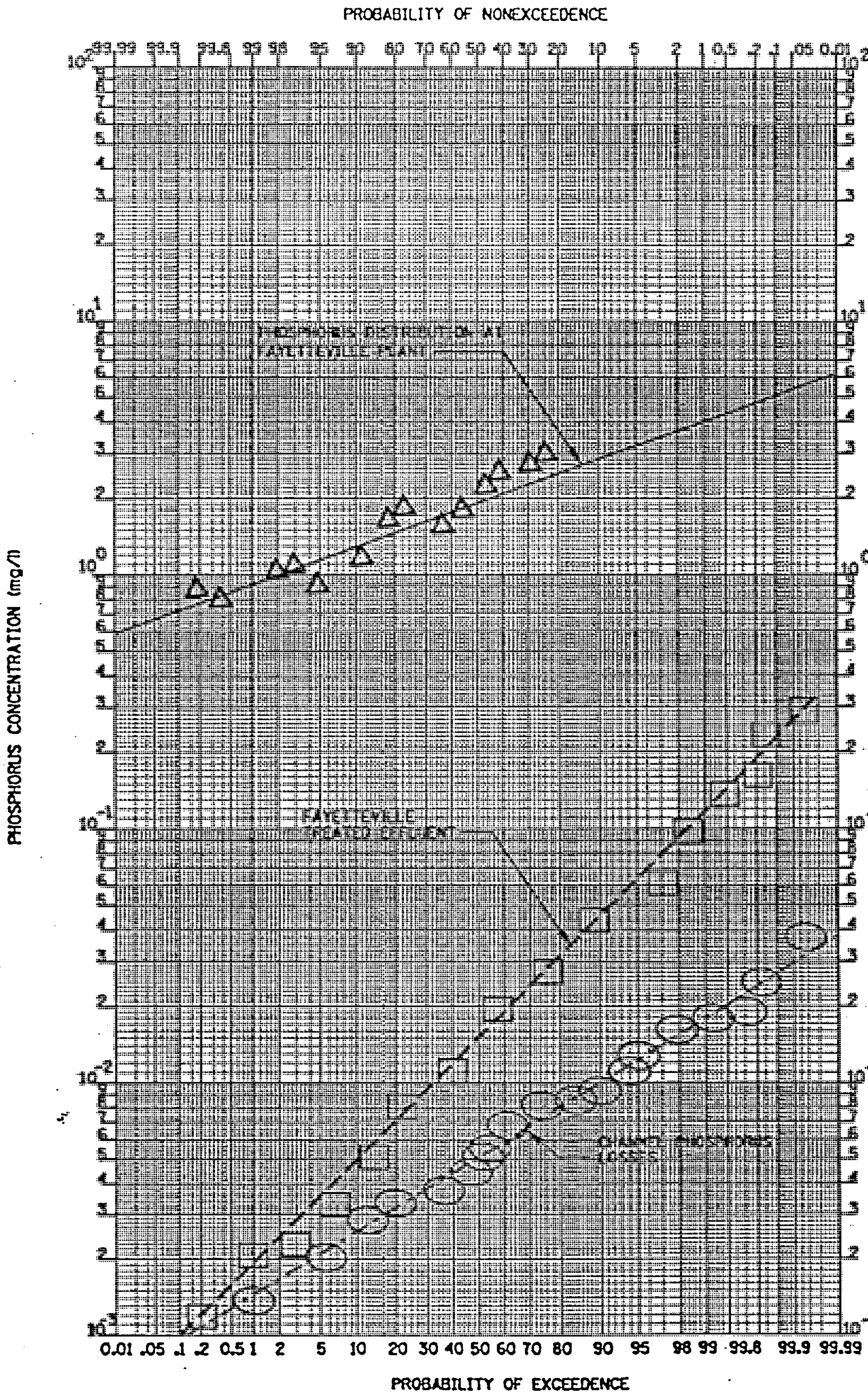


Figure 7. Various Phosphorus Concentration Probability Plots

with the Fayetteville wastewater treatment plant in operation. Figures 8 and 9 are plots showing the methods used to determine the appropriate number of simulations necessary to complete the Monte Carlo simulations for the low flow and combined distributions efforts respectively. These figures show that all distributions whether combined mathematically or obtained through computer modeling reached a point where further simulations had virtually no impact on the statistical distributions. These and subsequent loading calculations will be presented later. Utilizing the mean monthly pool and inflow data to Lake Tenkiller, shown in Figure 10 these distributions were converted into Vollenweider parameters to identify the annual lake eutrophication potential for given, randomly assessed load and lake conditions. Figure 11 is the probability graph for the Vollenweider Number and the Vollenweider Loading (Lp) Values for the historical with and without the addition of Fayetteville treated effluent. Figure 11 indicates that the two distributions are virtually identical for both the Loading Value (Lp) and Vollenweider Number distributions. Since the Vollenweider Number is a product of the Qs and the Lp values this distribution would exhibit a wider range of values. Figure 12 is additional comparison of these two data sets. The Vollenweider graph displays the placement of the individual values with respect to the various zones of eutrophication potential. The pie charts represent the percentage of those values in each of the three Vollenweider defined zones (eutrophic, mesotrophic

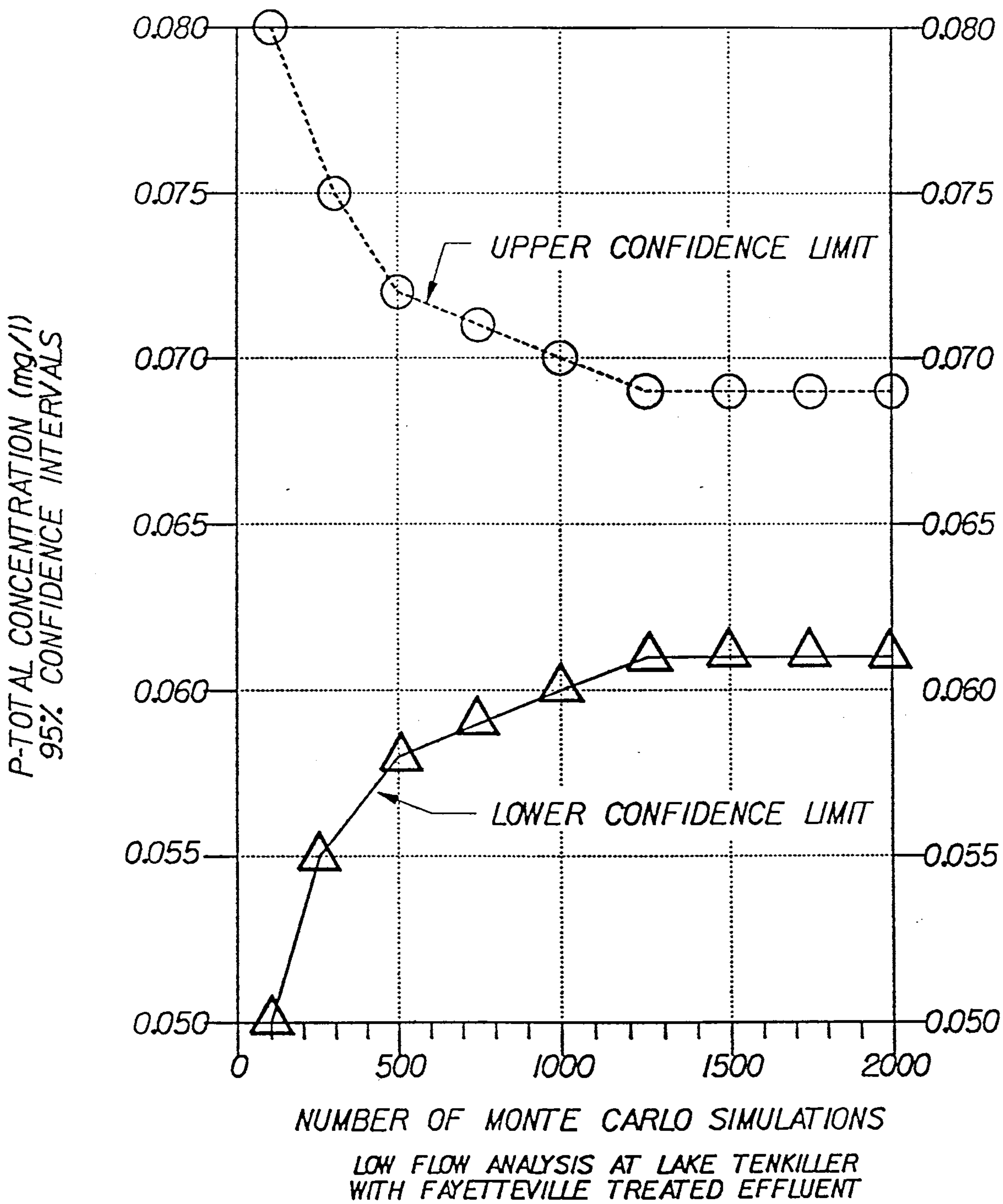


Figure 8. Precision Determination Curve for QUAL2E-UNCAS Monte Carlo Simulation Technique

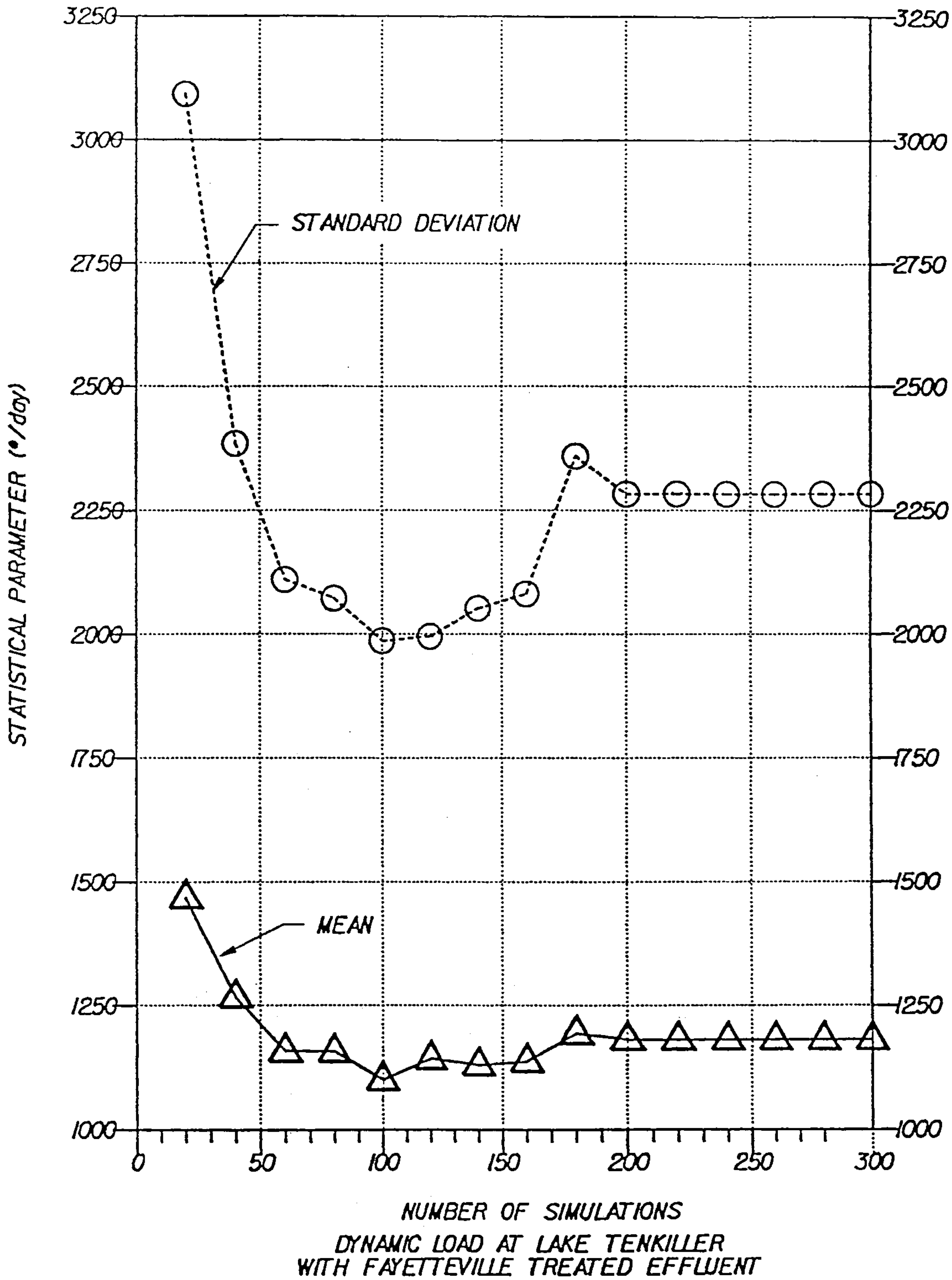


Figure 9. Precision Determination Curve for Randomly Accessed Probability Functions

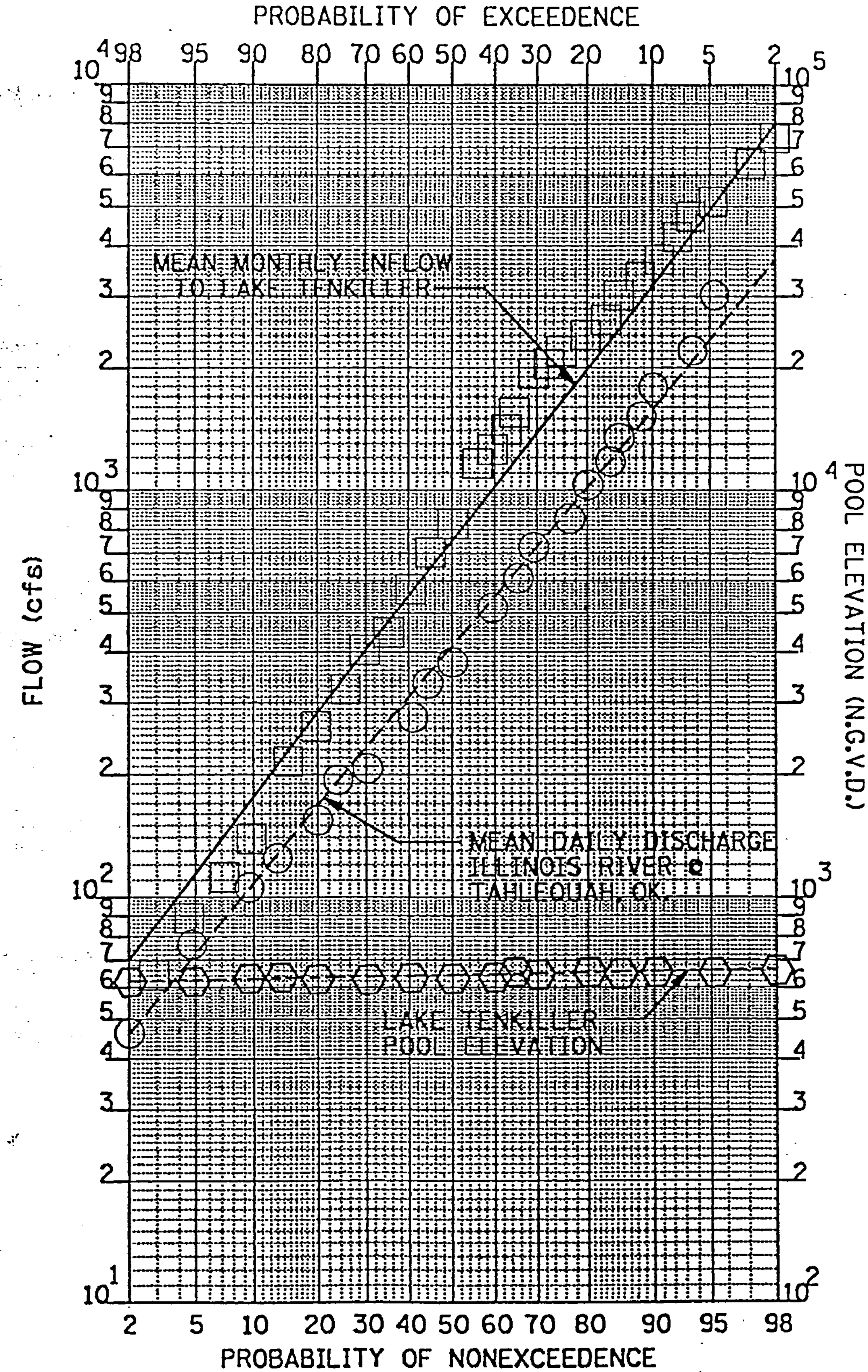


Figure 10. Mean Flow and Lake Tenkiller Pool Elevation Probability

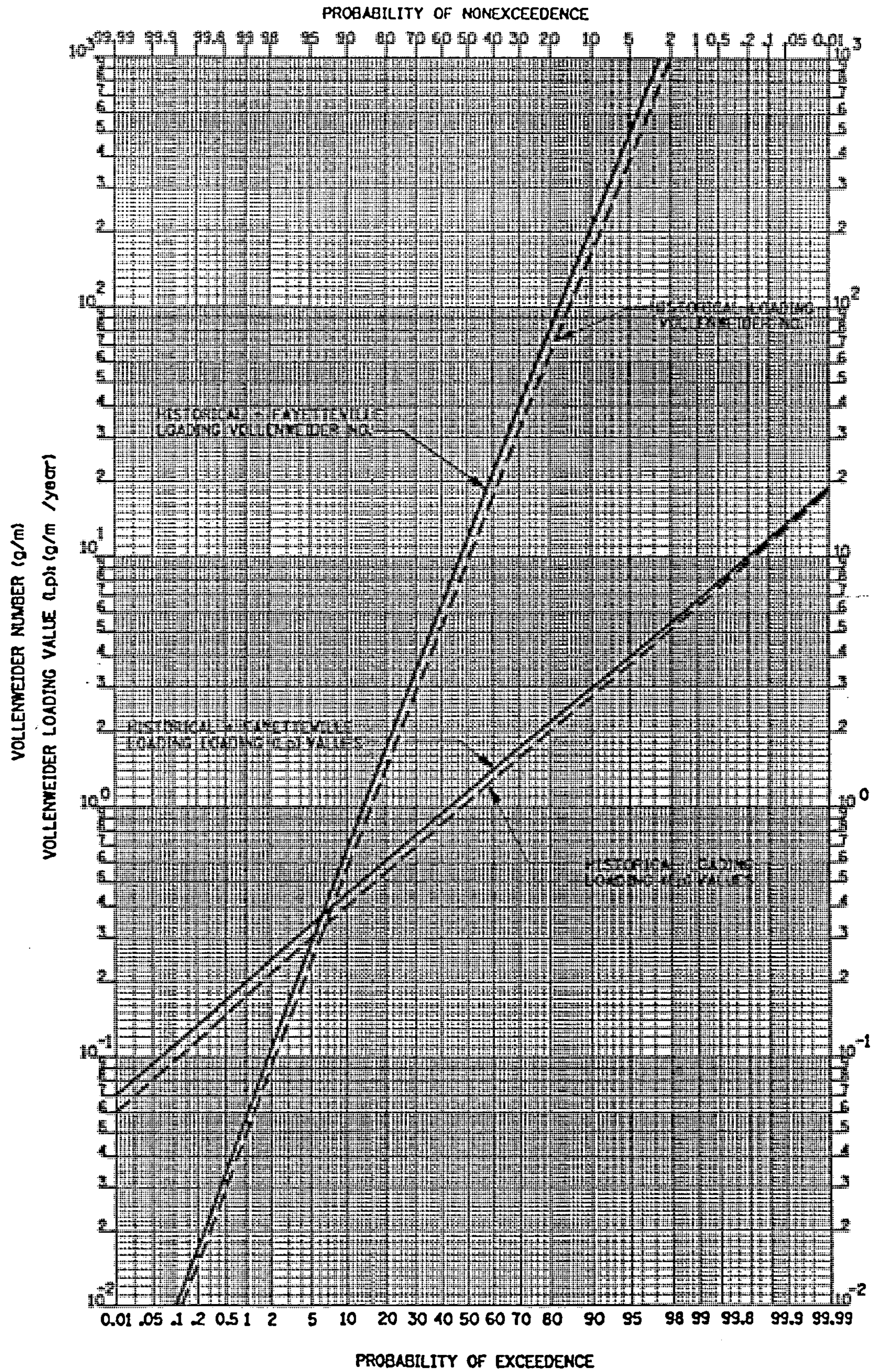


Figure 11. Vollenweider Parameter Distributions for Dynamic Loading Conditions

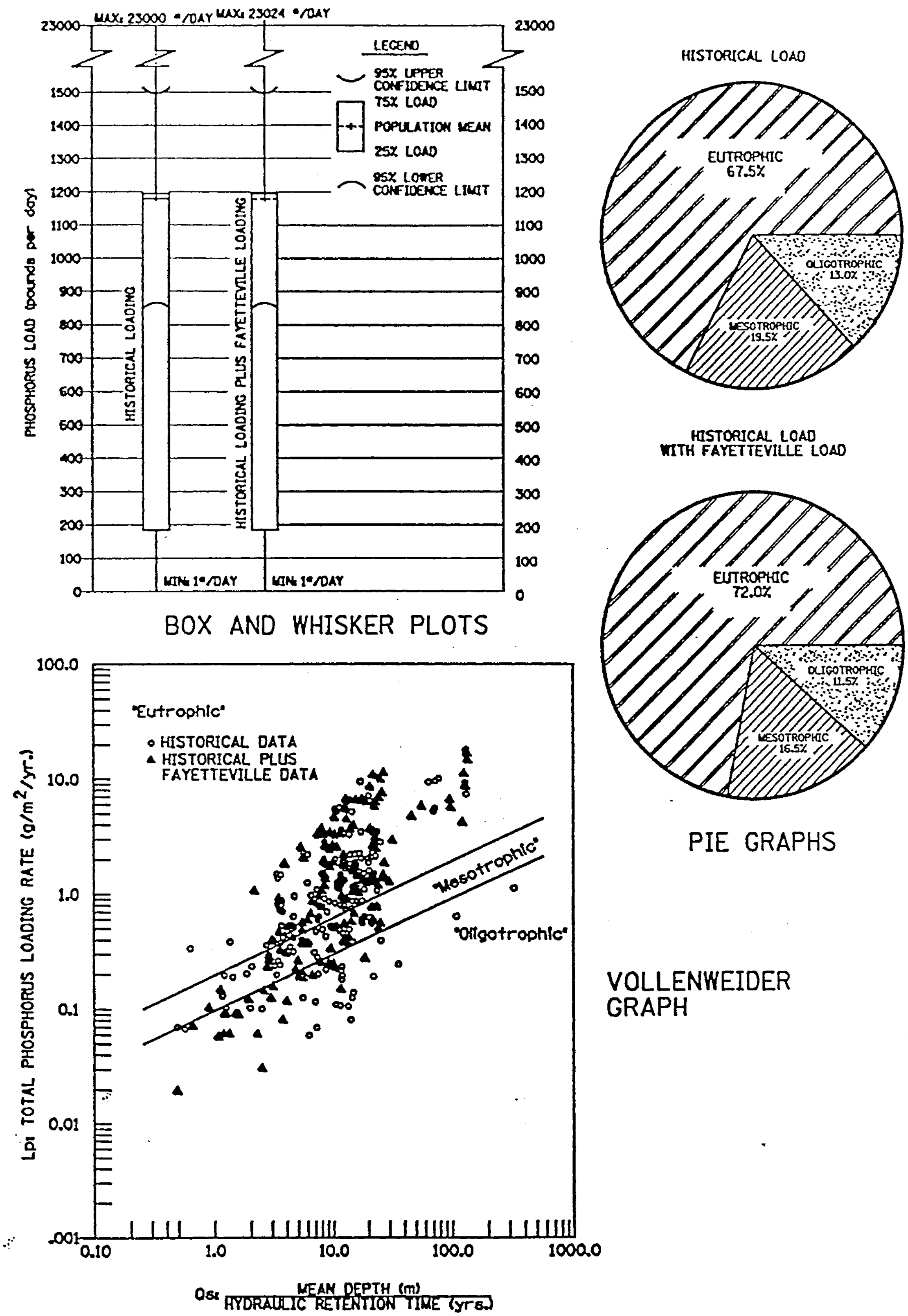


Figure 12. Historical Versus Historical Plus Fayetteville Graphical Comparisons

and oligotrophic). While the "box and whisker" plots show the overlapping of both the upper and lower 95% confidence intervals as well as the similarity of all statistical parameters.

Point and Non-Point Source Loading Distributions. The additional work conducted in this effort derived the distributions of point and non-point source loadings from Oklahoma and Arkansas. Figure 13 is the probability plot for the total run of the river loading at Lake Tenkiller with and without the Fayetteville treated effluent, the total point and non-point source load from all sources and the point and non-point source load from Oklahoma and Arkansas individually. This figure shows the domination of the total lake loading by the non-point sources and the relatively minor impacts of the point sources. Figure 14 are the "box and whisker" plots of these eight data sets. A comparison of the 95% confidence intervals for these data indicates the domination and wide range of confidence intervals of the non-point source loading. The States of Oklahoma and Arkansas contribute somewhat similar quantities of non-point source load. These plots also show the relatively minor impact of point source loading from both states.

Phosphorus Removal Alternatives. The effects of the phosphorus removal alternatives are illustrated in Figures 15 through 26. All graphics use the Fayetteville historical data augmented as the base case for comparison. Figure 15 is the Vollenweider Loading (Lp) Value probability plot for the

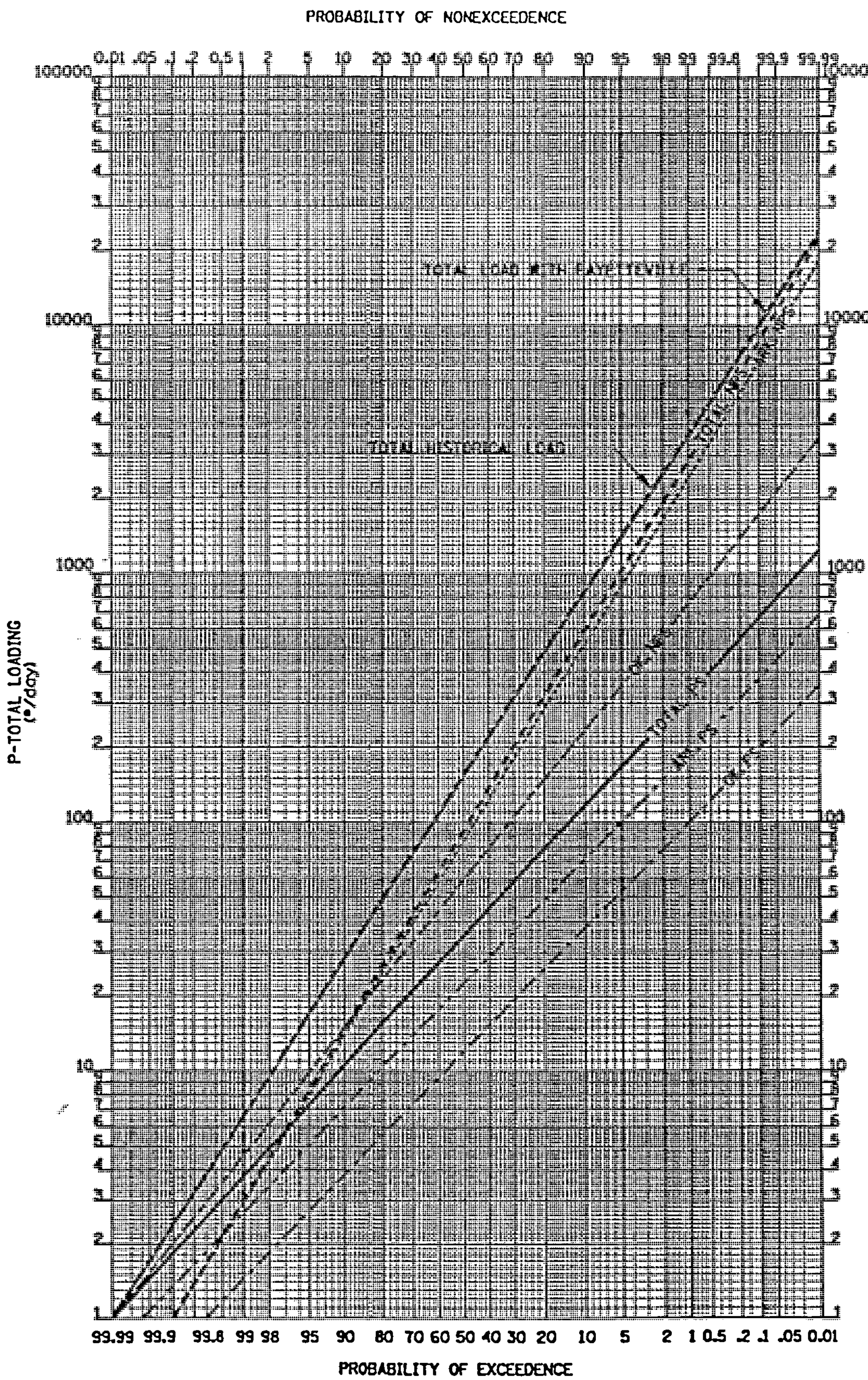


Figure 13. Loading Probability for Total Phosphorus at Lake Tenkiller for Point and Non-Point Sources

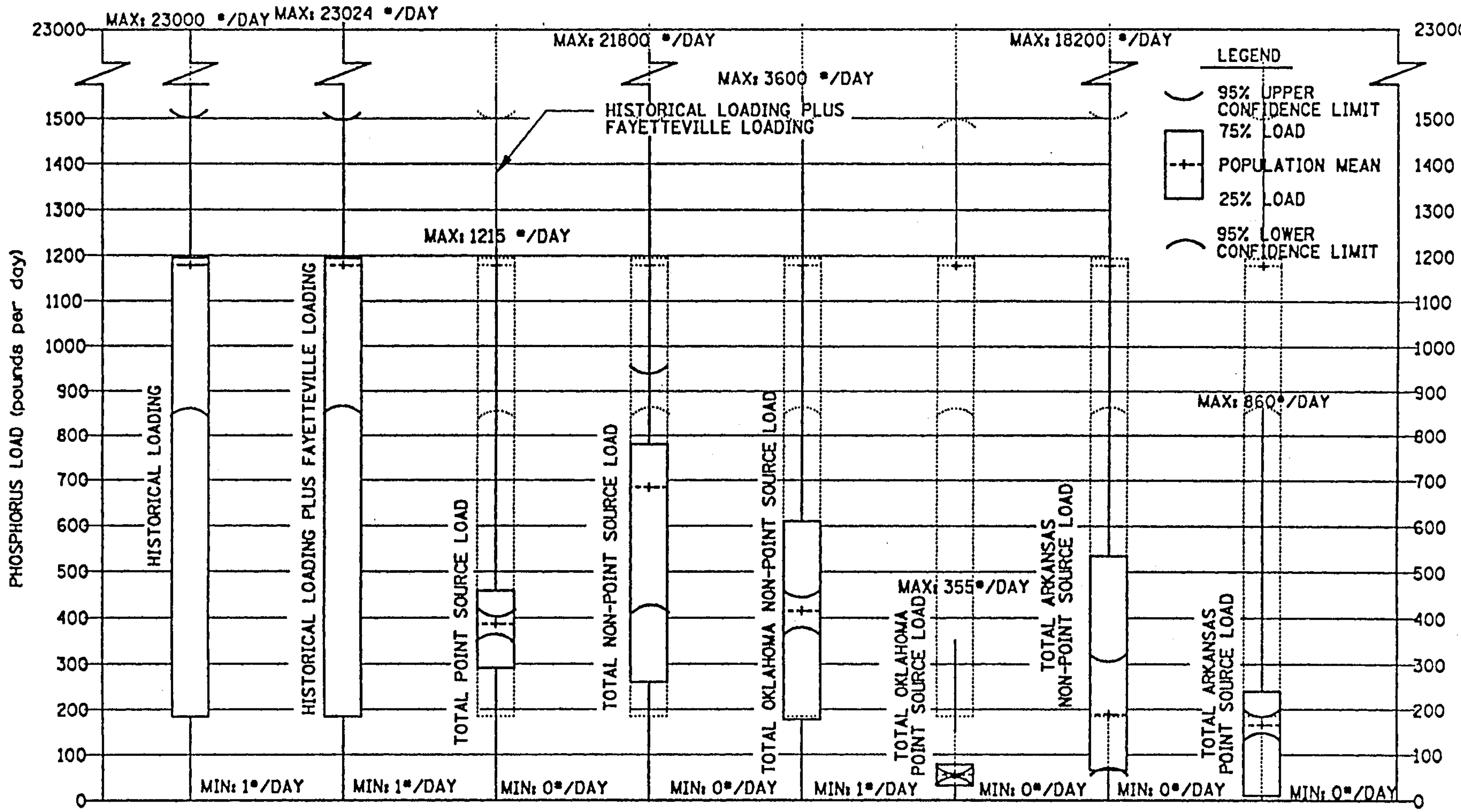


Figure 14. Lake Tenkiller Loading Inputs Statistical Parameters

historical loading, the historical loading with the addition of Fayetteville effluent, the 70% removal of total Oklahoma and Arkansas loads individually and the removal of 70% and 90% of the total combined load. Figure 16 is the probability plot of the Vollenweider Number for the same alternatives. Figures 17 and 18 are the "box and whisker" plots of the Vollenweider Number and Loading (Lp) Values distributions, respectively for the eight management alternatives examined in this effort. These plots show effectiveness of the simulated reduction of 70 and 90% of the total phosphorus loads. They also show how that projected individual state removal of phosphorus had a relatively minor reduction in anticipated eutrophication potential at Lake Tenkiller. Figures 19 through 24 are the Vollenweider graphs for these eight management alternatives. The distributions were converted to individual Vollenweider points and plotted. These figures show the relatively minor downward shift of the distribution for individual state removal options. However, there is a dramatic downward shift for total removal alternatives. Figures 25 and 26 are pie charts of these management alternatives taken from the Vollenweider plots previously presented. The percentage of points in each Vollenweider zone are displayed on the pie graphs.

Discussions

A summary of the overall results of this research is presented in Table XI. These results indicate that the Fay-

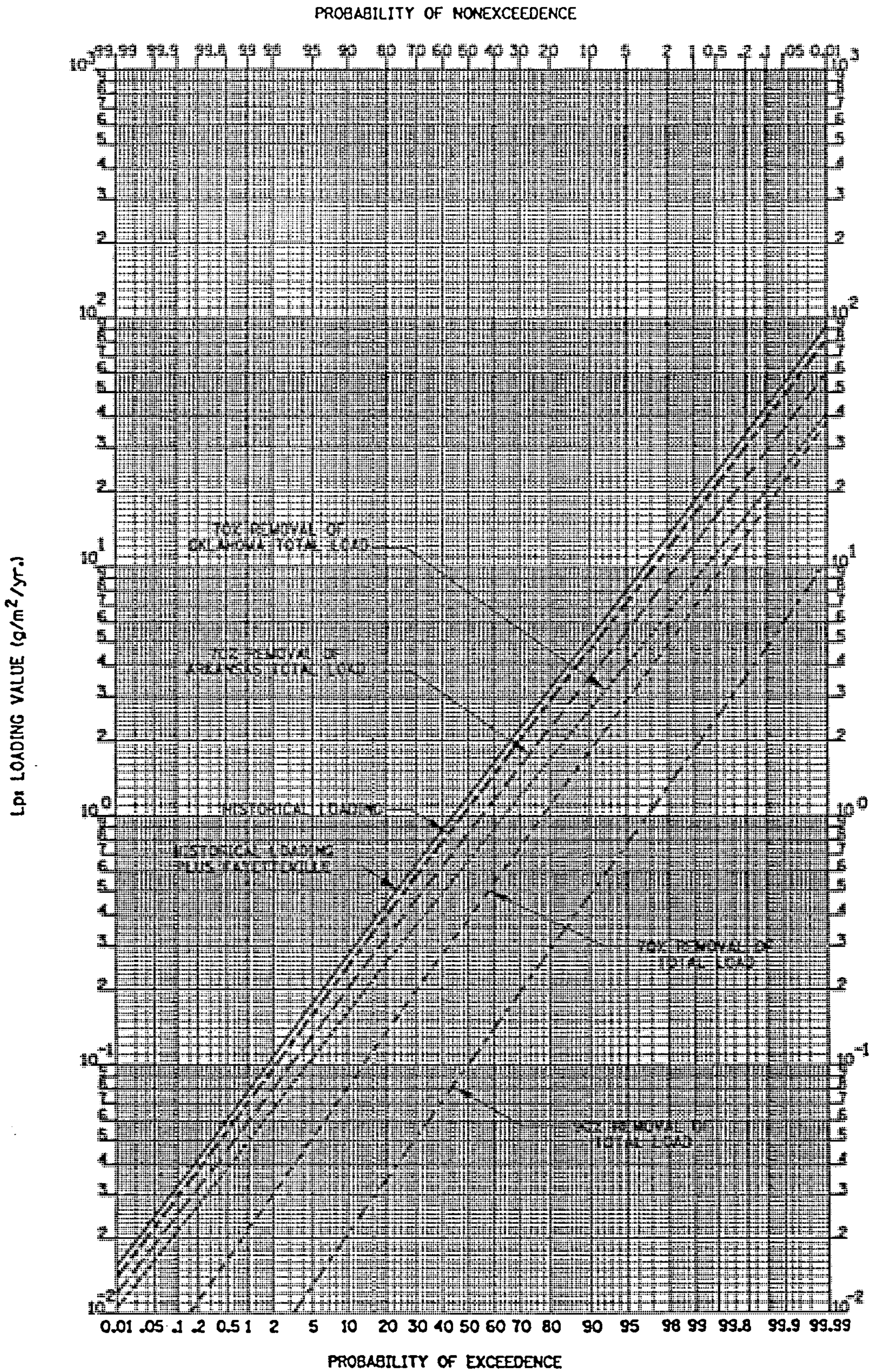


Figure 15. Vollenweider Loading Value (Lp) Distributions Management Alternatives

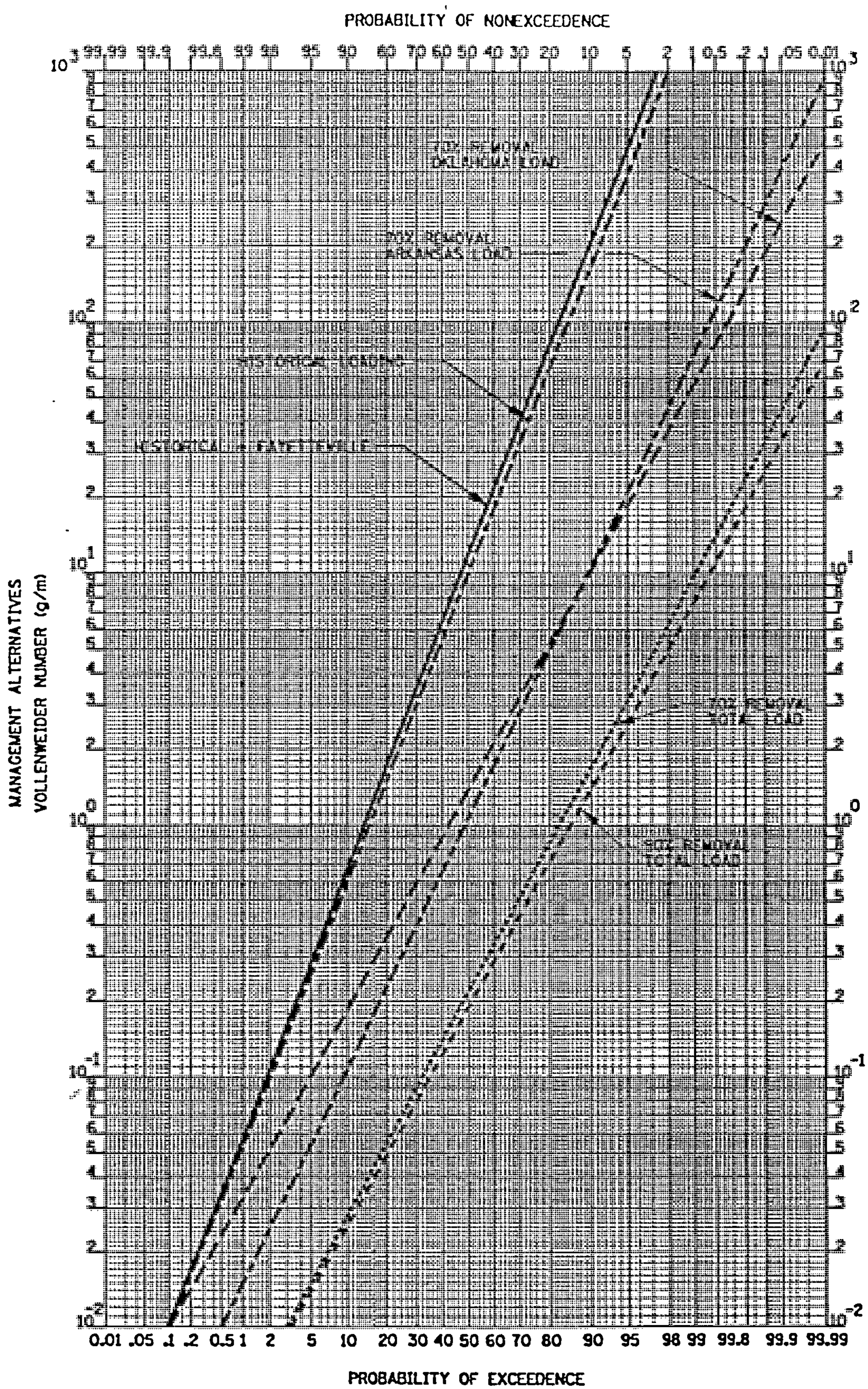


Figure 16. Vollenweider Number Probability Distribution Management Alternatives

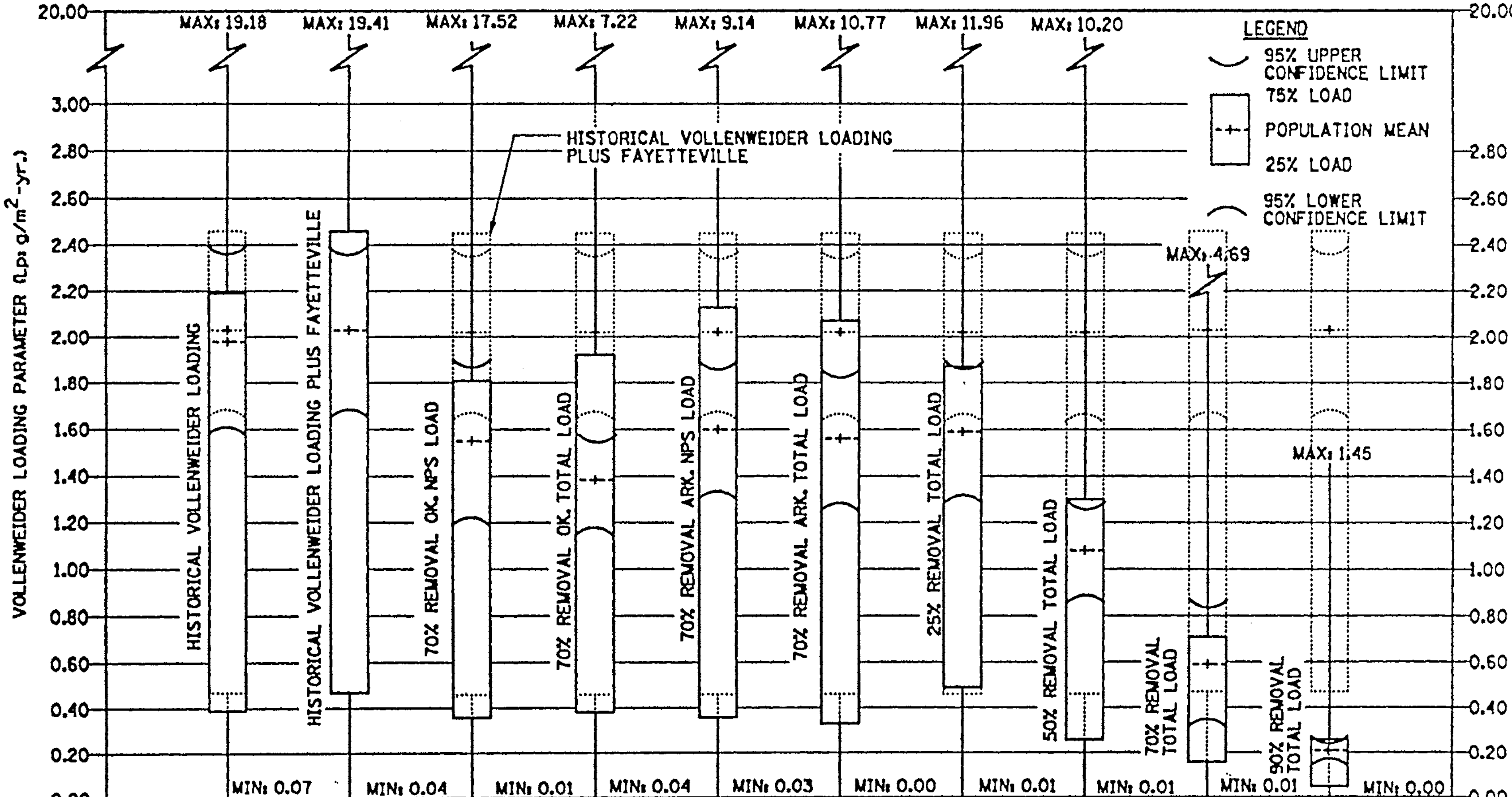


Figure 17. Lake Tenkiller Vollenweider Loading Ranges

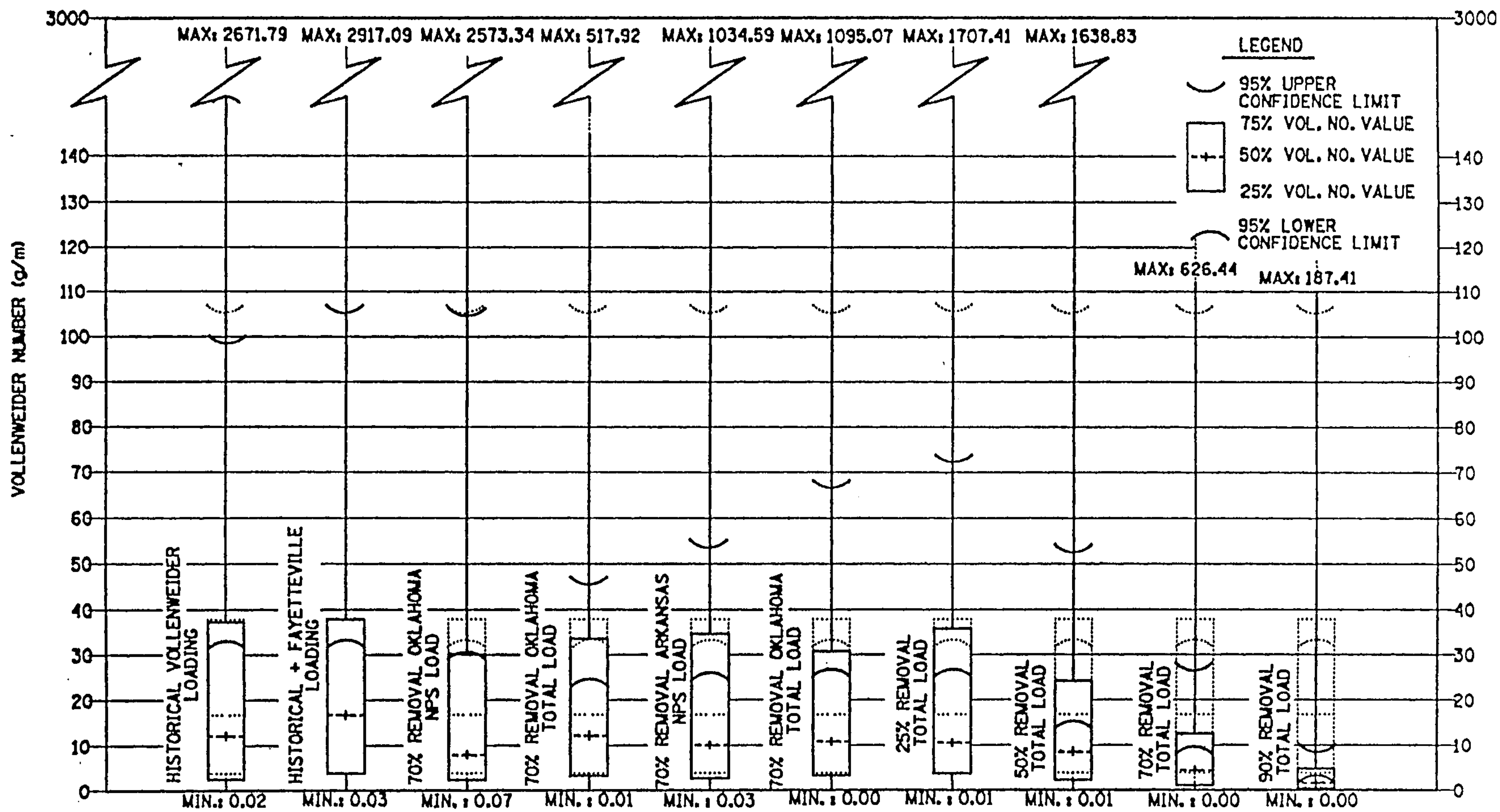


Figure 18. Lake Tenkiller Vollenweider Number

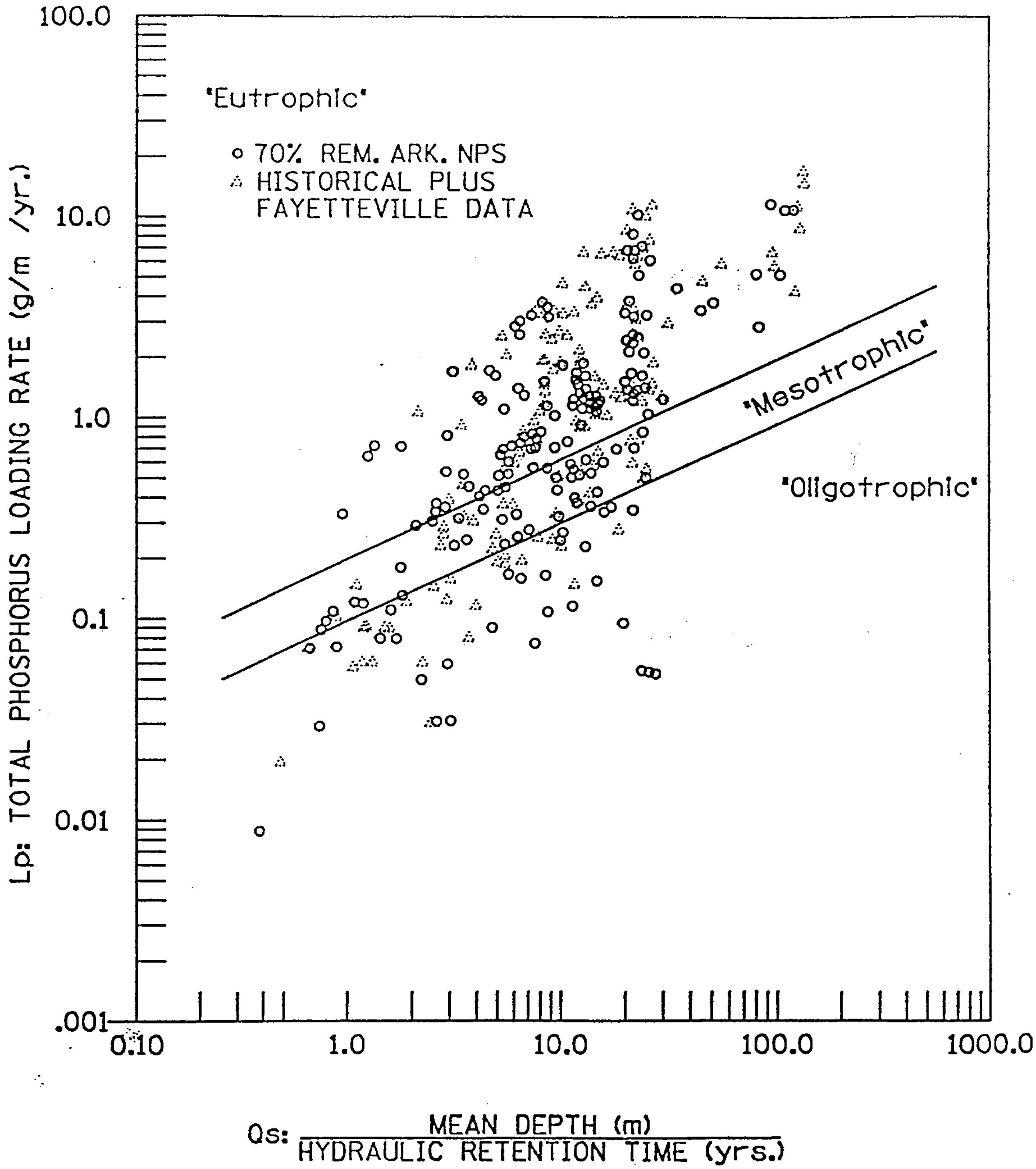


Figure 19. 70% Removal Arkansas Non-Point Source Loading

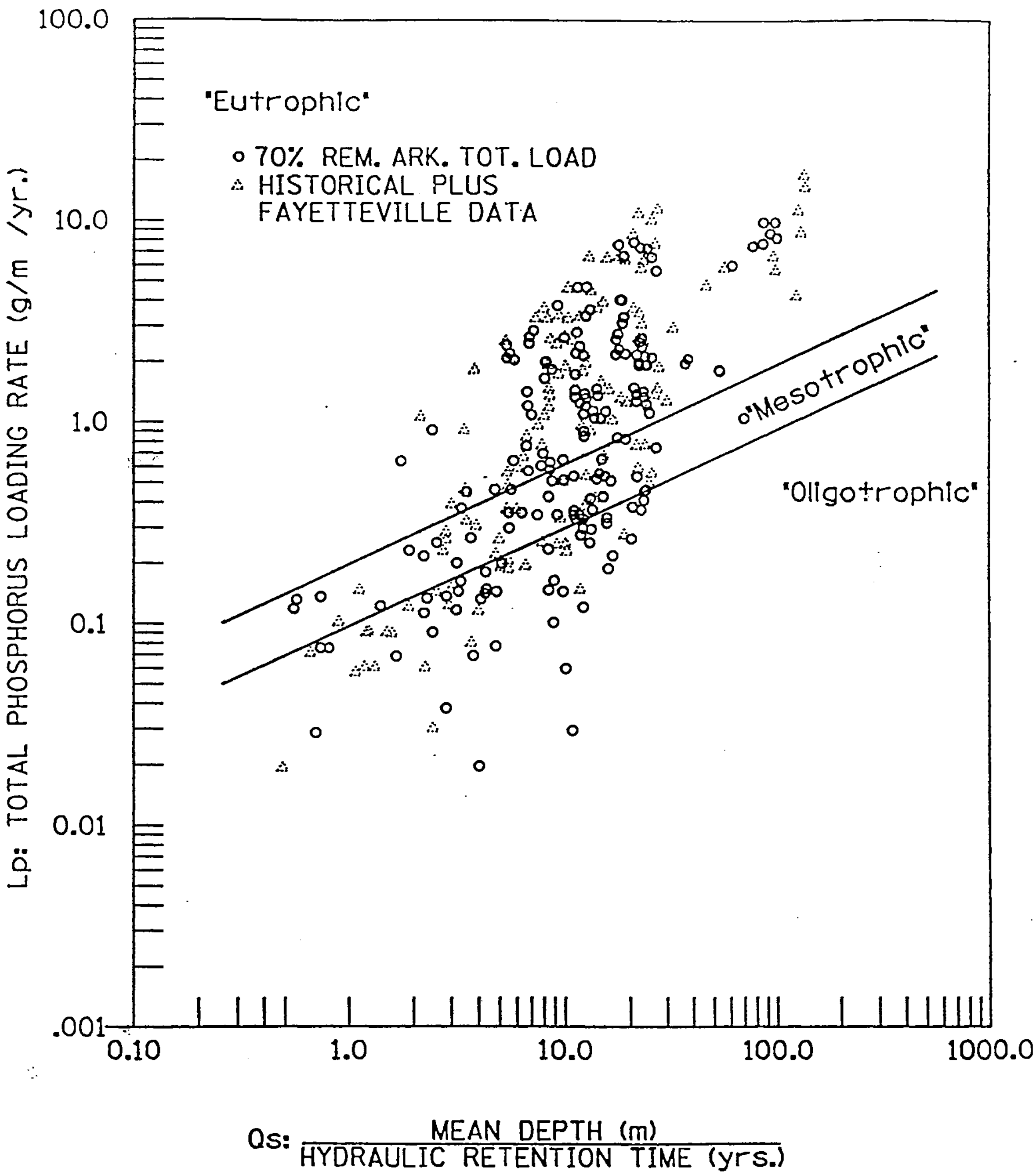


Figure 20. 70% Removal Arkansas Total Loading

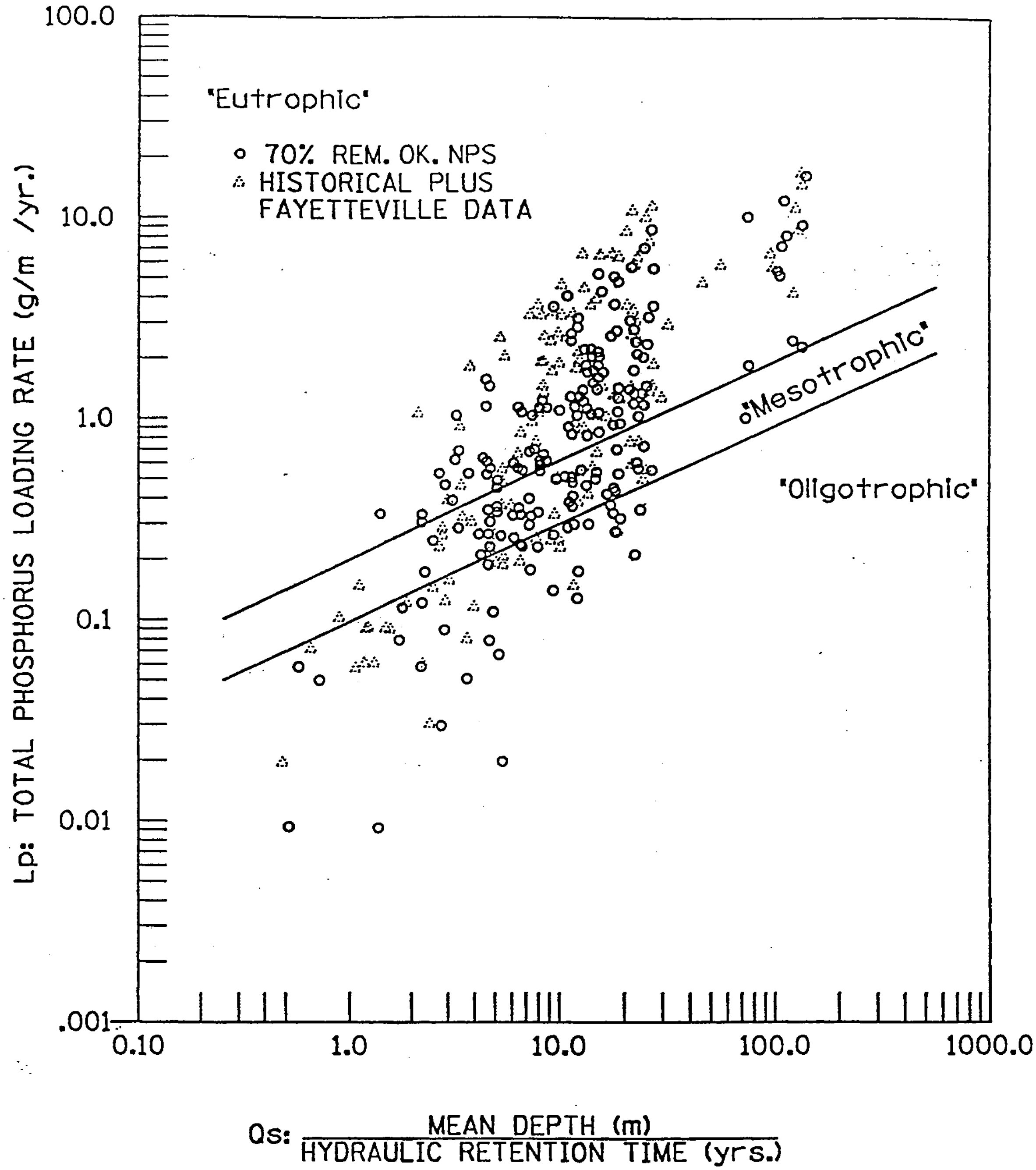


Figure 21. 70% Removal Oklahoma Non-Point Source Loading

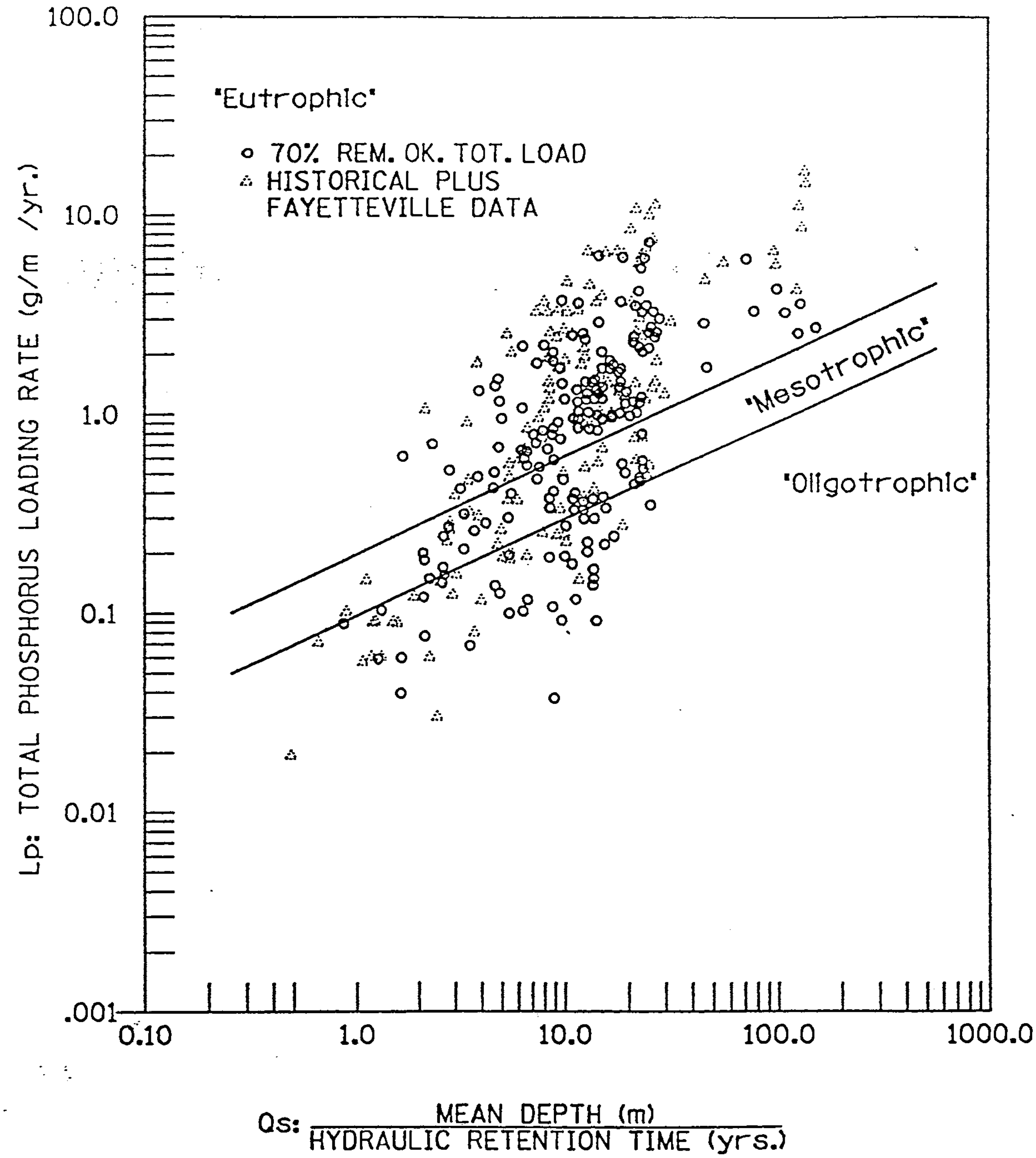


Figure 22. 70% Removal Oklahoma Total Loading

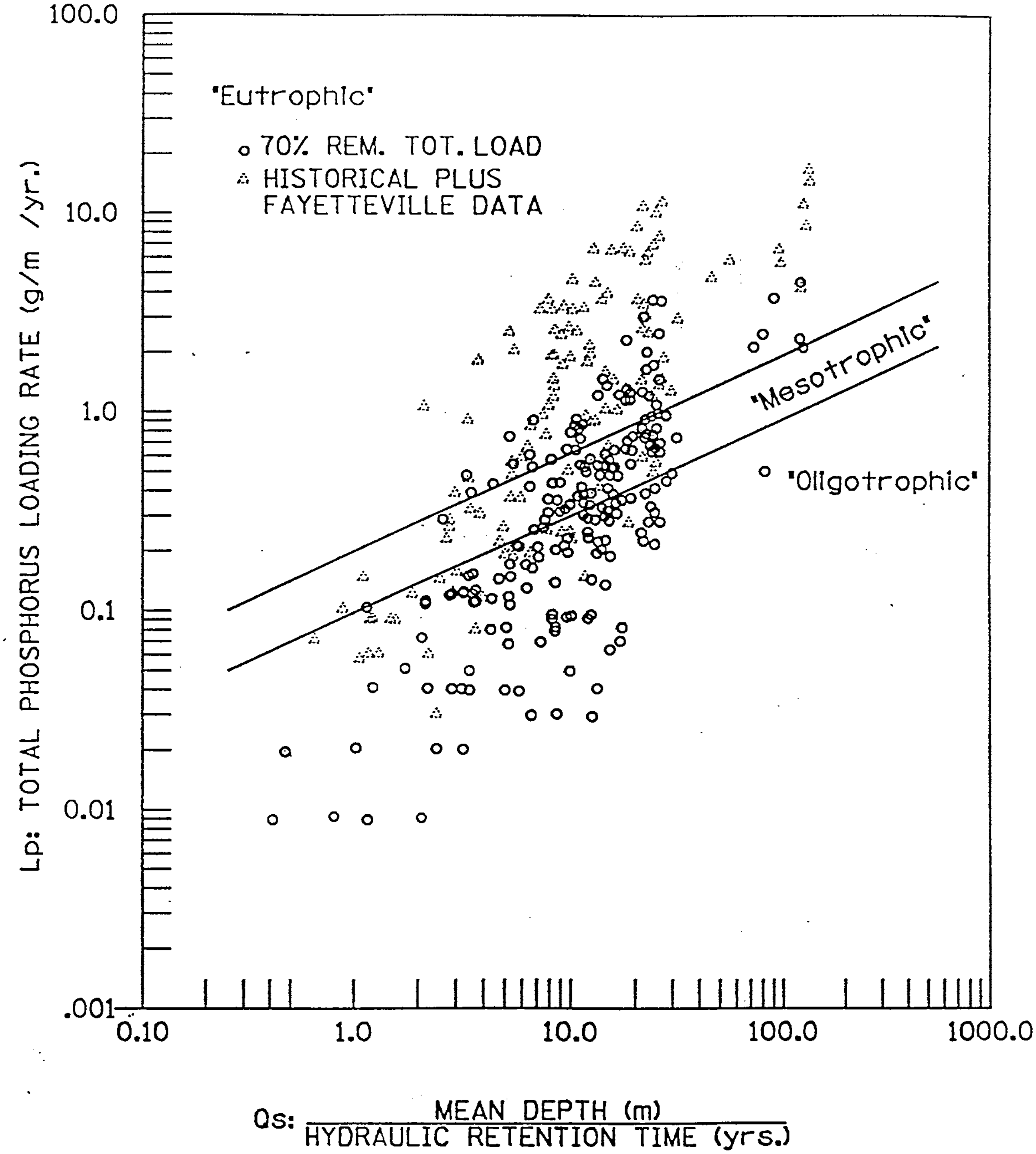
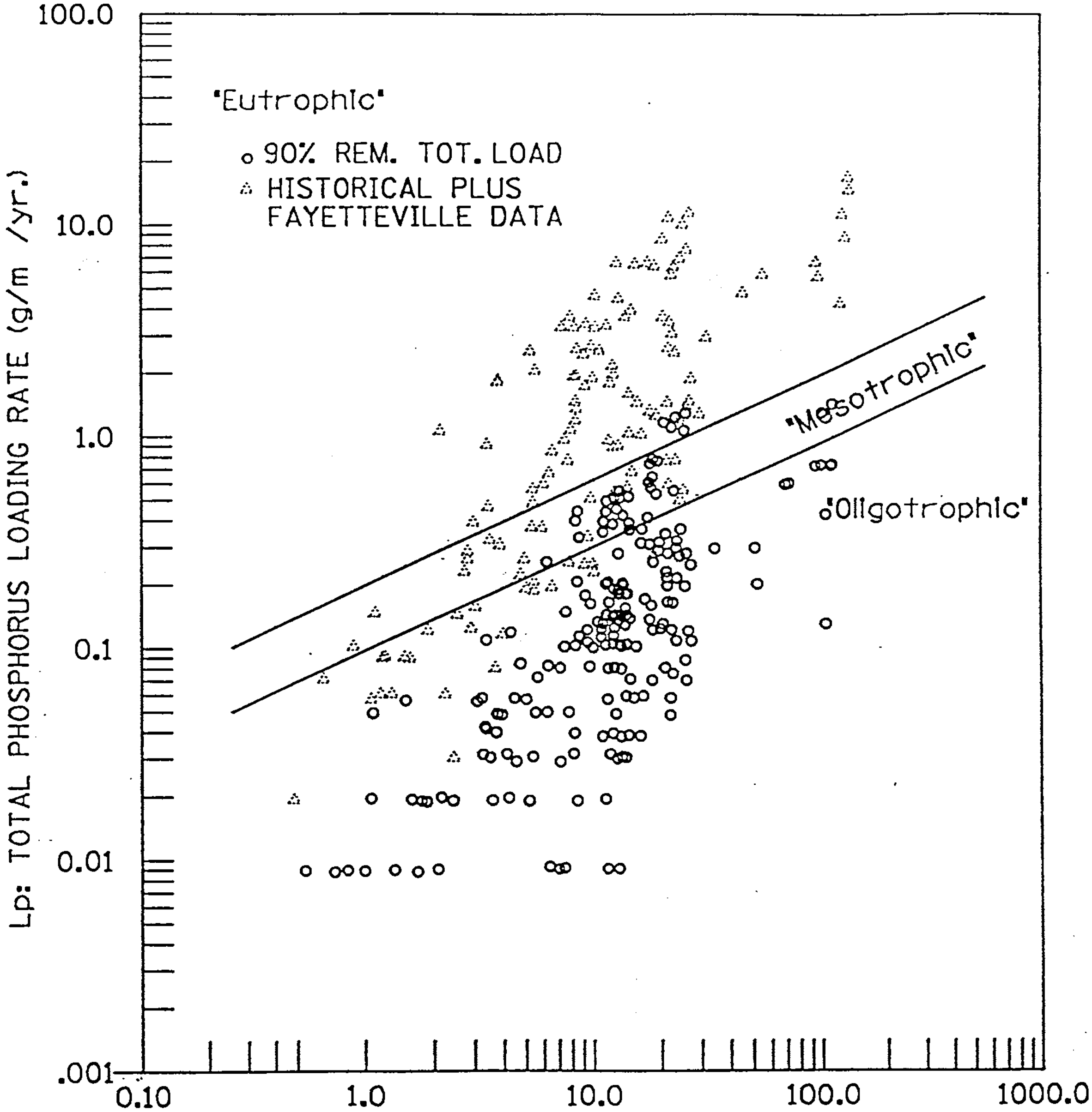


Figure 23. 70% Removal Total Load



$$Qs: \frac{\text{MEAN DEPTH (m)}}{\text{HYDRAULIC RETENTION TIME (yrs.)}}$$

Figure 24. 90% Removal Total Load

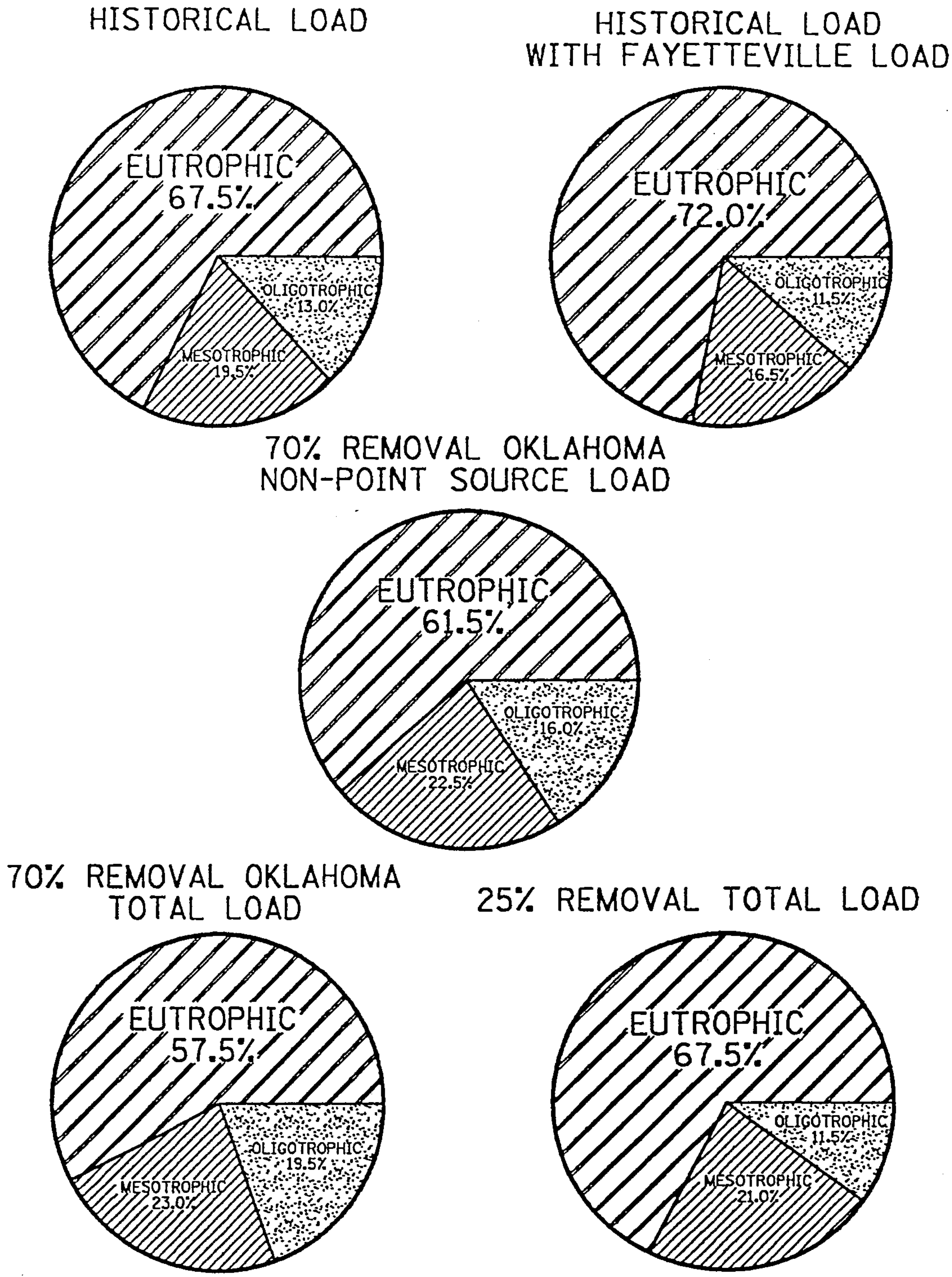


Figure 25. Pie Graphs of Various Management Alternatives Compared to Historic Conditions

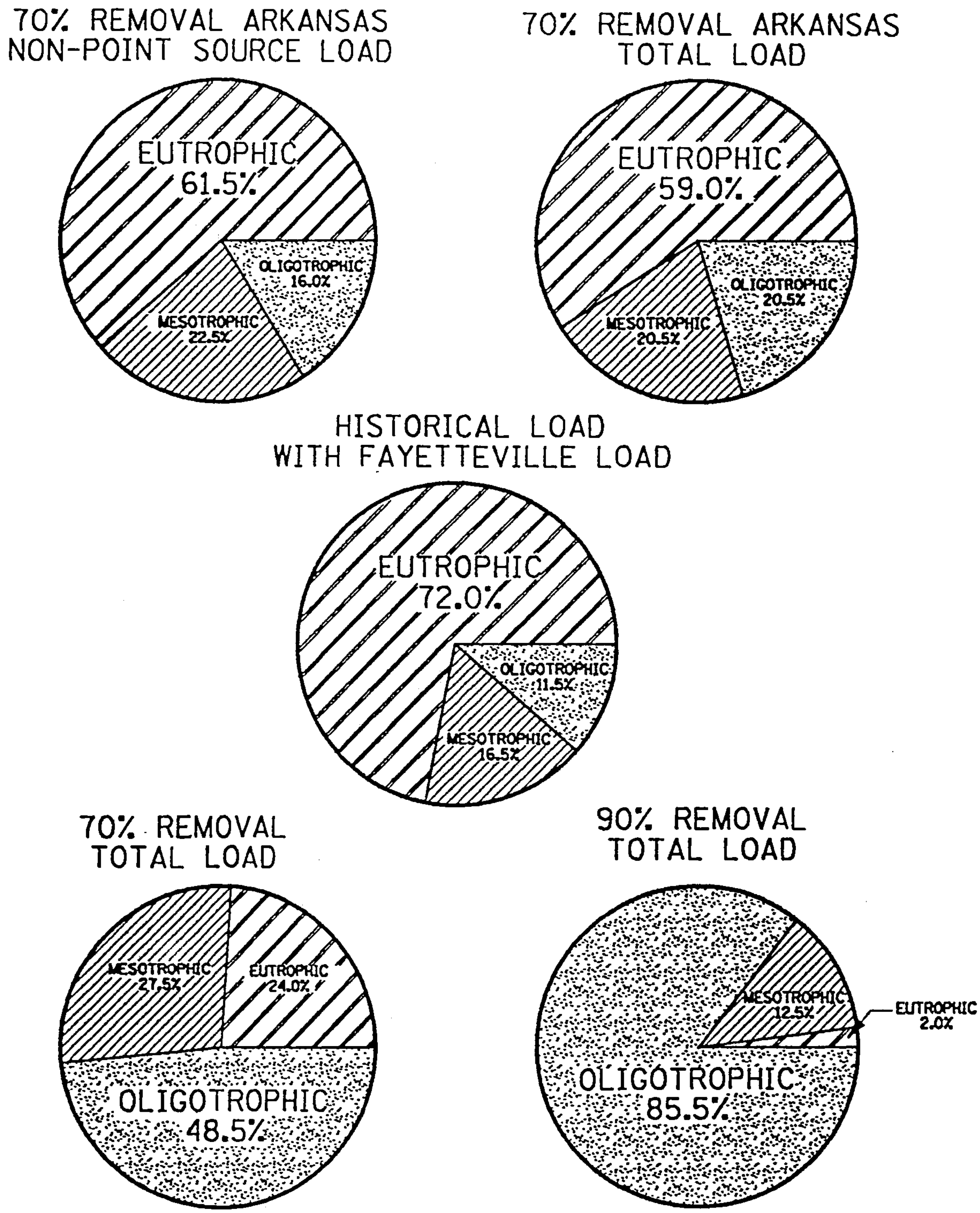


Figure 26. Management Alternatives Compared With Historical Plus Fayetteville Loading

etteville treated effluent would have a minimal impact on the eutrophication potential in Lake Tenkiller. The research also indicates the effectiveness of total phosphorus removal versus individual state efforts in reducing eutrophication. Figures 12 and 13 clearly show that both the run of the river distributions with and without the treated Fayetteville waste are almost identical. In Figure 12 the "box and whisker" confidence intervals overlap, therefore the distributions are statistically similar at the 95% certainty level. Similarly, the probability distributions in Figure 13 virtually overlay each other. The relatively low volume as well as load projected from Fayetteville combined with the natural phosphorus removal mechanisms occurring in the Illinois River and its' tributaries results in minimal impact at the reservoir.

With respect to Vollenweider parameters Lake Tenkiller currently has a significant eutrophication problem as indicated in Figure 12. The associated pie charts show that a slight increase in eutrophication will result with the addition of the treated effluent.

The main sources of phosphorus in the Illinois River watershed are from non-point sources as is shown in Figures 13 and 14. The non-point sources clearly dominate the probability graphs in Figure 13 and the statistical parameters in the "box and whisker" plots in Figure 14. Oklahoma and Arkansas seem to contribute approximately equal amounts of non-point source contamination. This explains why individual state management options had little impact on lowering

TABLE XI

SUMMARY OF FINDINGS

Description	Vollenweider Parameters Mean Vol. No.	Mean Qs Value	Mean Lp Value	Mean P-load (#/day)	% Improvement Mean P-Load
Historical Loading	69.38	16.88	1.98	1180.91	Base Case
Historical Loading w/Fayetteville Treated Effluent	69.84	16.08	2.07	1181.67	-0.06
70% Reduction Ok. NPS Load	68.14	17.51	1.55	875.48	25.9
70% Reduction Ark. NPS Load	39.77	15.76	1.60	663.88	43.8
70% Reduction Ok. Total Load	34.98	16.86	1.36	816.23	30.9
70% Reduction Ark. Total Load	46.72	15.95	1.56	561.12	52.5
50% Reduction Total Load	34.03	16.14	1.08	531.47	55.0
70% Reduction Total Load	18.48	16.43	0.59	320.60	72.9
90% Reduction Total Load	6.08	16.59	0.21	95.65	91.9

the eutrophication potential as illustrated by Figures 15-26. A simulated reduction of 70 and 90% of the total basin-wide phosphorus load has the most significant impact on reducing eutrophication at Lake Tenkiller. Figures 19 through 24 show the notable shift in the distributions towards the oligotrophic range as the percentage of total phosphorus was removed.

Conclusions

The stochastic method of determining phosphorus loading distributions utilizing historical water quality, discharge and lake hydraulic and operational data employed in this research:

1. Provided a simpler, more workable and less time consuming alternative to analyses of eutrophication than was possible with dynamic wave and/or complex watershed models.

2. Due to the fact that eutrophication is a long term time-dependent process this method can be used in conjunction with steady-state, low flow models to ascertain the potential impact of various point and non-point source phosphorus loads.

3. Allows the analysis of an entire distribution of loadings instead of means or extremes which is essential in defining appropriate range of watershed management alternatives.

The results of the various derived phosphorus loading data sets and representations of these distributions by the graphical techniques employed in this study indicate that:

1. Lake Tenkiller Ferry currently appears to have a significant eutrophication problem due to non-point source phosphorus loading.

2. Treated wastewater effluent from Fayetteville, Arkansas would have a minimal effect on increasing the eutrophication potential in Lake Tenkiller.

3. Oklahoma and Arkansas appear to contribute equal amounts of phosphorus load to Lake Tenkiller and the Illinois River.

4. Individual state removal of phosphorus seem to have some beneficial impact on reducing phosphorus load levels, but, the removal of the large percentages of the total load appears necessary to bring eutrophication in Lake Tenkiller under control.

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APPENDIX A

SAMPLE VOLLENWEIDER CALCUALTIONS

AND LAKE TENKILLER DATA

TABLE XII

POOL ELEVATION-SURFACE AREA, STORAGE VOLUME RELATIONSHIP FOR LAKE TENKILLER FERRY

Pool Elev.	Surface Area (acres)	Storage Volume (ac.-ft.)	Pool Elev.	Surface Area (acres)	Storage Volume (ac.-ft.)
590	6,910	250,800	636	13,600	706,900
592	7,100	264,900	638	13,900	734,700
594	7,320	279,400	640	14,300	762,500
596	7,530	294,200	642	14,600	791,900
598	7,760	309,600	644	15,100	821,300
600	7,990	325,200	646	15,500	852,000
602	8,230	341,600	648	15,900	883,200
604	8,490	358,200	650	16,400	915,600
606	8,730	375,400	652	16,900	949,000
608	9,020	393,100	654	17,400	983,000
610	9,300	411,400	656	17,900	1,018,800
612	9,590	430,500	658	18,400	1,054,600
614	9,890	449,900	660	18,900	1,092,200
616	10,200	470,200	662	19,400	1,130,400
618	10,500	490,700	664	20,000	1,169,200
620	10,800	512,100	666	20,500	1,210,200
622	11,200	533,900	668	21,100	1,251,200
624	11,500	556,800	670	21,600	1,294,400
626	11,800	580,000	672	22,200	1,338,200
628	12,200	604,100	674	22,800	1,382,800
630	12,500	628,700	676	23,400	1,429,800
632	12,900	654,100	678	24,000	1,477,000
634	13,200	680,300	680	24,700	1,525,000

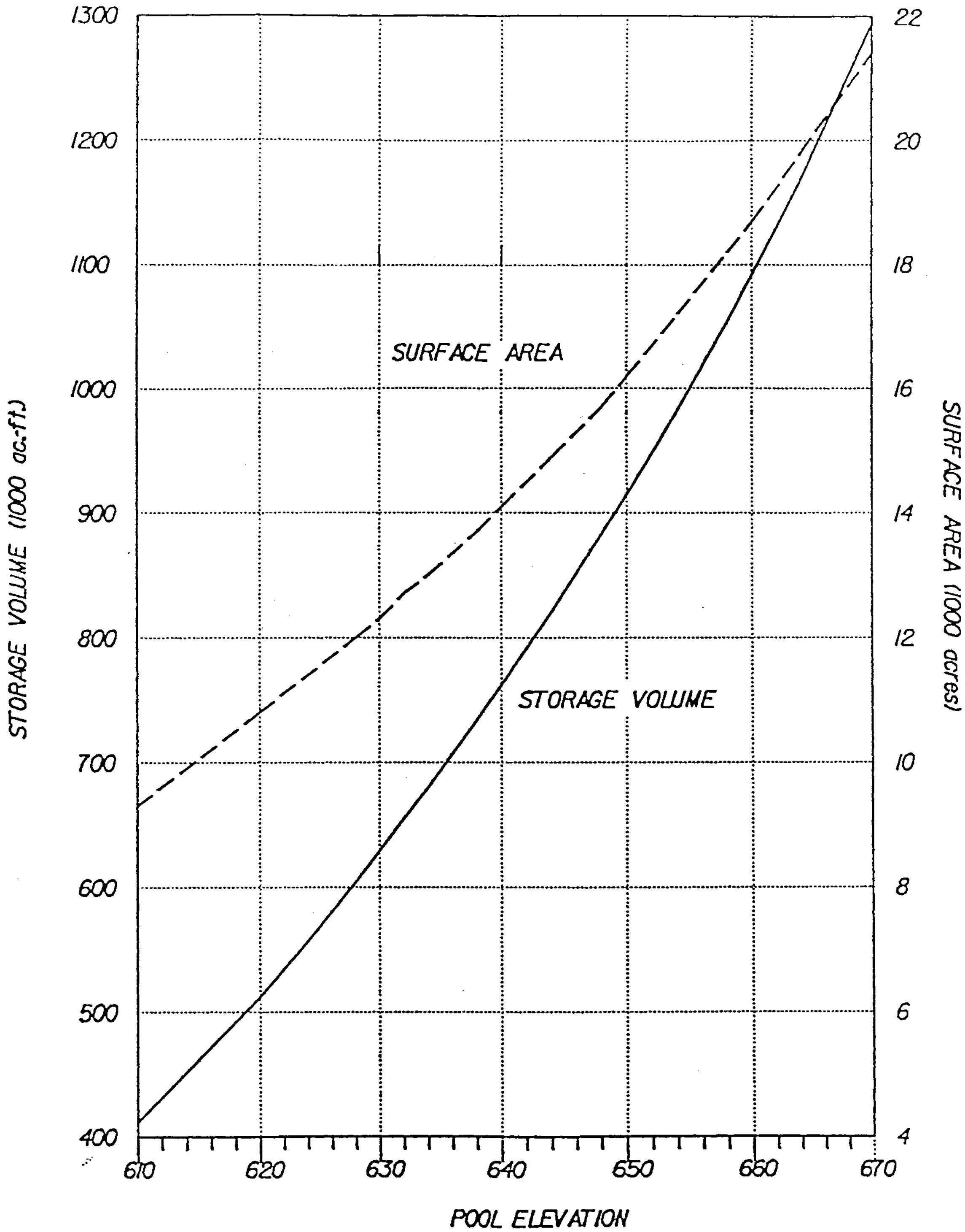

Figure 27. Pool Elevation vs. Area/Storage Volume Curve
Lake Tenkiller Ferry

LOADING, Lp MINIMUM CONDITION

LAKE DATA FOR SAMPLE PROBLEM

Problem Data	Value	Units (English)	Value	Units (Metric)
Pool Elev.	667.0	-	-	-
Surface Area	20,800	Acres	8.418×10^7	Meters^2
Volume	5.361×10^{10}	Ft.^{3}	-	-
Depth	59.17	Feet	18.04	Meters
Inflow	100	C.F.S.	-	-
P-Total Conc.	0.005	mg/l	-	-

I. Calculate the Hydraulic Residence Time: (Tw)

$$Tw = \frac{\text{Volume (ft}^3\text{)}}{\text{Annual Inflow (cfs)}} = \frac{5.361 \times 10^{10}\ (\text{ft}^3)}{100\ (\text{cfs})}$$

Tw = 536,100,000 secs. = 17.00 years

II. Compute (Qs) = Mean Depth / Tw (Independent Axis)

$$Qs = \frac{18.04\ \text{m}}{17.00\ \text{years}} = 1.06\ \text{meters per year}$$

III. Compute Annual Inflow, Qy (ft^3)

1 year = 31,540,000 seconds
Qy = 100 cfs X 31,540,000 seconds per year
Qy = 3,154,000,000 cubic feet per year

IV: Compute Lp: Loading Value (Dependent Axis)

$$Lp = \frac{28.311}{\text{ft}^3} \times \frac{1\text{g}}{1000\text{mg}} \times \frac{.005\ \text{mg}}{1} \times \frac{1}{8.418 \times 10^7\,\text{m}^2} \times 3.154 \times 10^9\ \frac{\text{ft}^3}{\text{yr.}}$$

Lp = 0.005 g/m^2/year

Vollenweider Point: (Qs,Lp) = (1.06,0.005)
Vollenweider Number: 0.0053 g/m

Figure 28. Sample Vollenweider Calculation
Condition No. 1

LOADING, Lp MAXIMUM CONDITION

LAKE DATA FOR SAMPLE PROBLEM

Problem Data	Value	Units (English)	Value	Units (Metric)
Pool Elev.	620.0	-	-	-
Surface Area	10,800	Acres	4.317×10^7	Meters^2
Volume	2.231×10^{10}	Ft.^{3}	-	-
Depth	47.42	Feet	14.45	Meters
Inflow	8,500	C.F.S.	-	-
P-Total Conc.	0.415	mg/l	-	-

I. Calculate the Hydraulic Residence Time: (Tw)

$$Tw = \frac{\text{Volume (ft}^3\text{)}}{\text{Annual Inflow (cfs)}} = \frac{2.231 \times 10^{10} \text{ (ft}^3\text{)}}{8{,}500 \text{ (cfs)}}$$

Tw = 2,624,362 secs. = 0.08 years

II. Compute (Qs) = Mean Depth / Tw (Independent Axis)

$$Qs = \frac{14.45 \text{ m}}{0.08 \text{ years}} = 180.6 \text{ meters per year}$$

III. Compute Annual Inflow, Qy (ft^3)

1 year = 31,540,000 seconds

Qy = 8,500 cfs X 31,540,000 seconds per year

Qy = 2.6809×10^{11} cubic feet per year

IV: Compute Lp: Loading Value (Dependent Axis)

$$Lp = \frac{28.311}{\text{ft}^3} \times \frac{\text{lg}}{1000\text{mg}} \times \frac{.451 \text{ mg}}{\text{l}} \times \frac{1}{4.371 \times 10^7 \text{m}^2} \times 2.6809 \times 10^{11} \frac{\text{ft}^3}{\text{yr.}}$$

Lp = 72.1 g/m^2/year

Vollenweider Point: (Qs,Lp) = (180.6,72.1)

Vollenweider Number: 13,021.3 g/m

Figure 29. Sample Vollenweider Calculation Condition No. 2

SAMPLE VOLLENWEIDER CALCULATION

LAKE DATA FOR SAMPLE PROBLEM

Problem Data	Value	Units (English)	Value	Units (Metric)
Pool Elev.	632.0	-	-	-
Surface Area	12,900	Acres	43,824,549	$Meters^2$
Volume	$1.5768x10^{10}$	$Ft.^3$	-	-
Depth	50.71	Feet	15.5	Meters
Inflow	500	C.F.S.	-	-
P-Total Conc.	0.05	mg/l	-	-

I. <u>Calculate Hydraulic Residence Time: (Tw)</u>

$$Tw = \frac{\text{Volume } (ft^3)}{\text{Annual Inflow (cfs)}} = \frac{1.5768x10^{10}\ (ft^3)}{500\ (cfs)}$$

$Tw = 5.6985 \times 10^7$ secs. = 1.81 years

II. Compute (Qs) = Mean Depth / Tw (Independent Axis)

$$Qs = \frac{15.5 \text{ m}}{1.81 \text{ years}} = 8.56 \text{ meters per year}$$

III. Compute Annual Inflow, Qy (ft^3)

1 year = 31,540,000 seconds
Qy = 500 cfs X 31,540,000 seconds per year
Qy = 1.5768×10^{10} cubic feet per year

IV: Compute Lp: Loading Value (Dependent Axis)

$$Lp = \frac{28.311}{ft^3} \times \frac{1g}{1000mg} \times \frac{0.05 \text{ mg}}{1} \times \frac{1}{43{,}824{,}549m^2} \times 1.5768X10^{10}\ \frac{ft^3}{yr.}$$

Lp = 1.61 g/m^2/year

Vollenweider Point: (8.56,1.61)
Vollenweider Number: 13.78 g/m

Figure 30. Sample Vollenweider Calculation
Condition No. 3

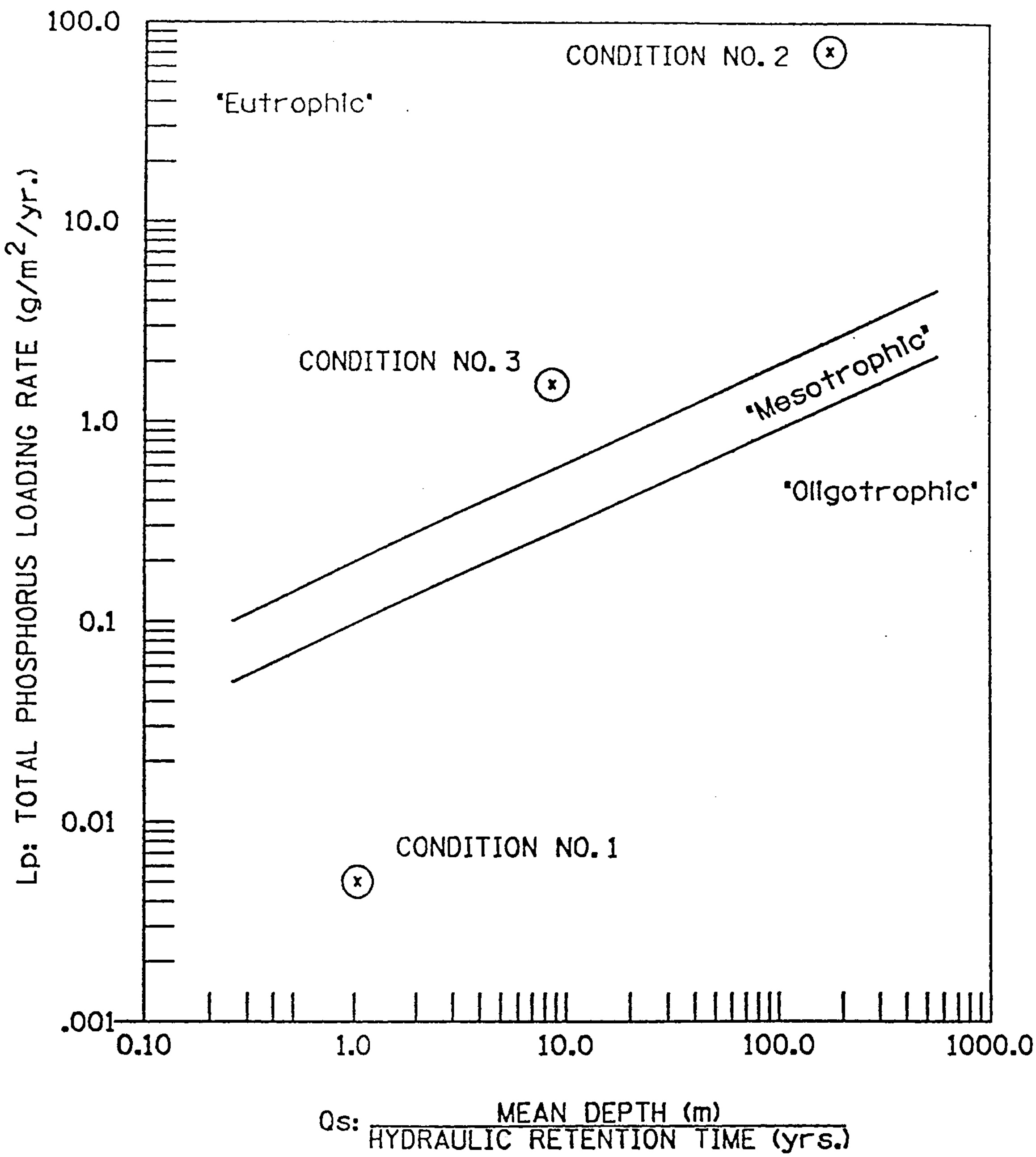

Figure 31. Plot of Sample Vollenweider Calculations

APPENDIX B

U.S.G.S. WATER QUALITY GAUGES: ILLINOIS RIVER

VARIABLE DATA PROBABILITY PLOTS

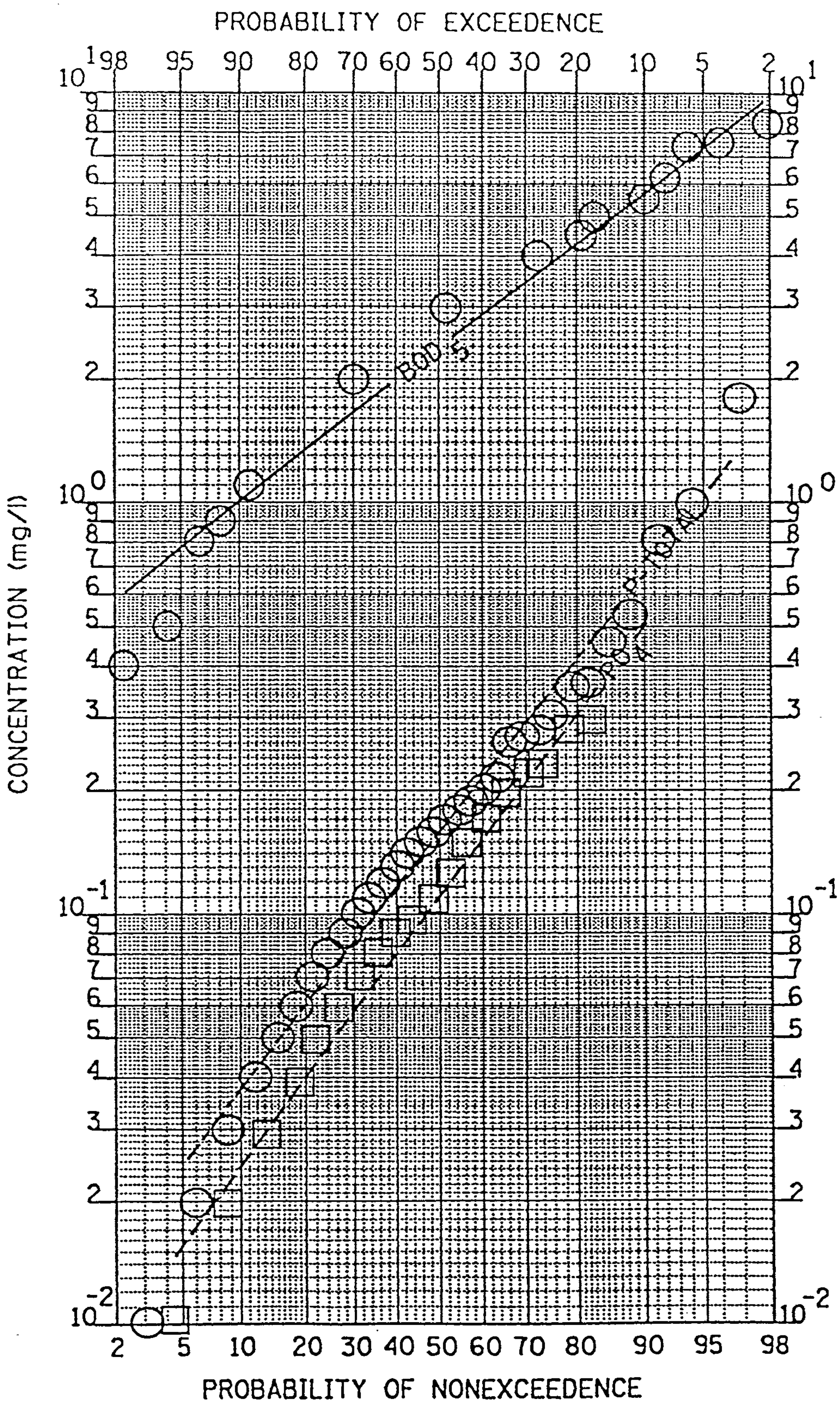

Figure 32. U.S.G.S. Gauge on Illinois River at Savoy, Arkansas

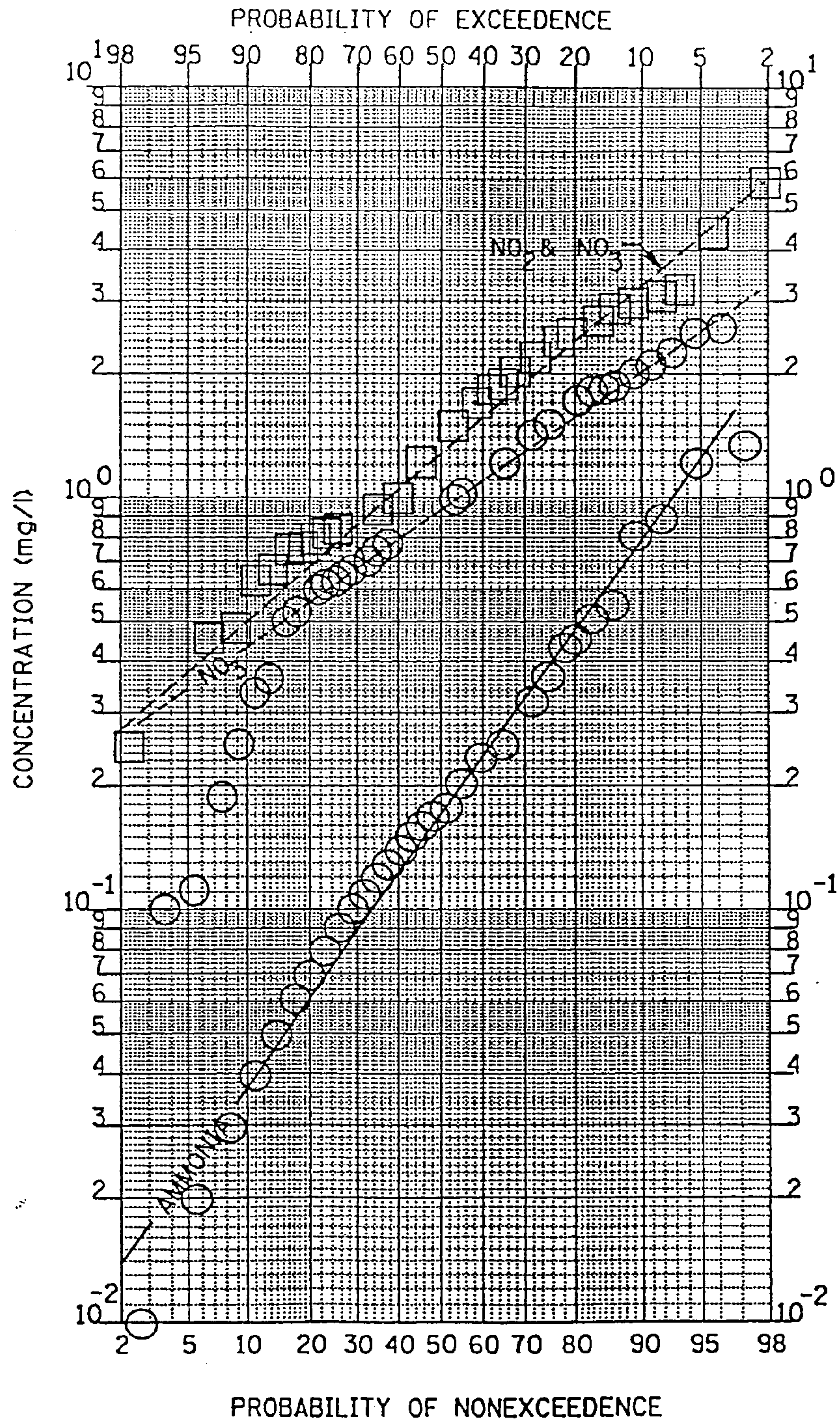

Figure 33. U.S.G.S. Gauge on Illinois River at Savoy, Arkansas

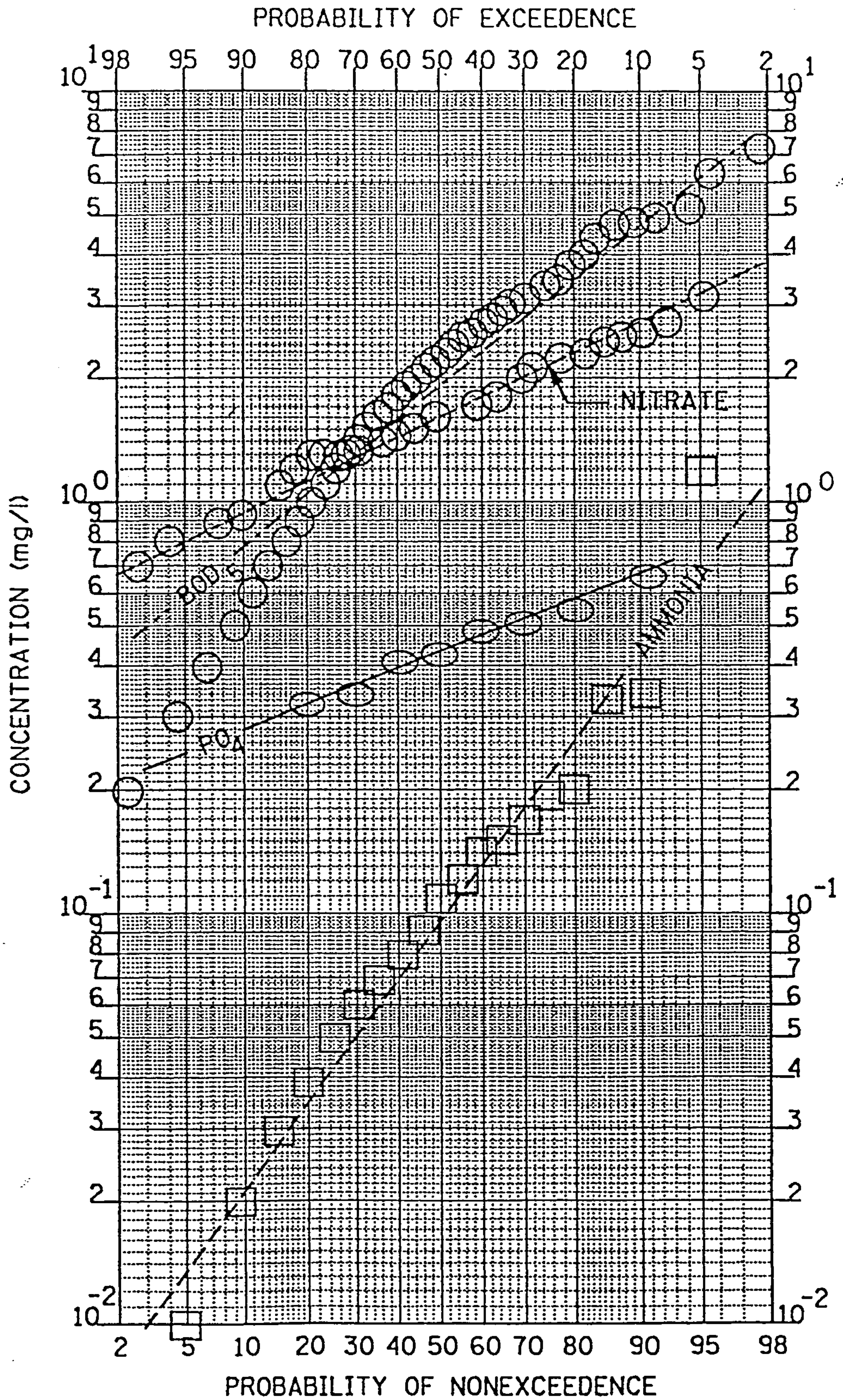

Figure 34. U.S.G.S. Gauge on Illinois River at Siloam Springs, Arkansas

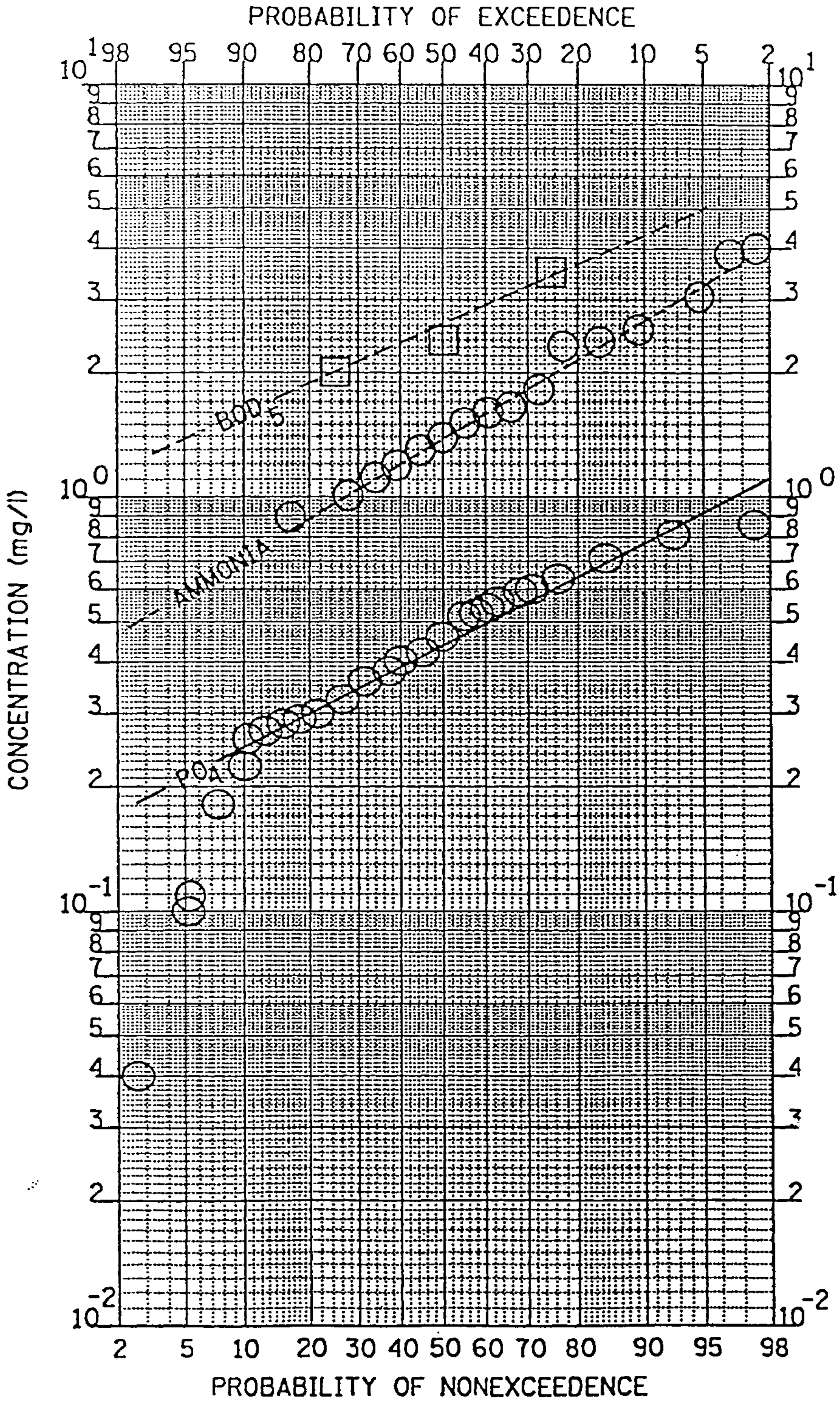

Figure 35. U.S.G.S. Gauge on Illinois River at Watts, Oklahoma

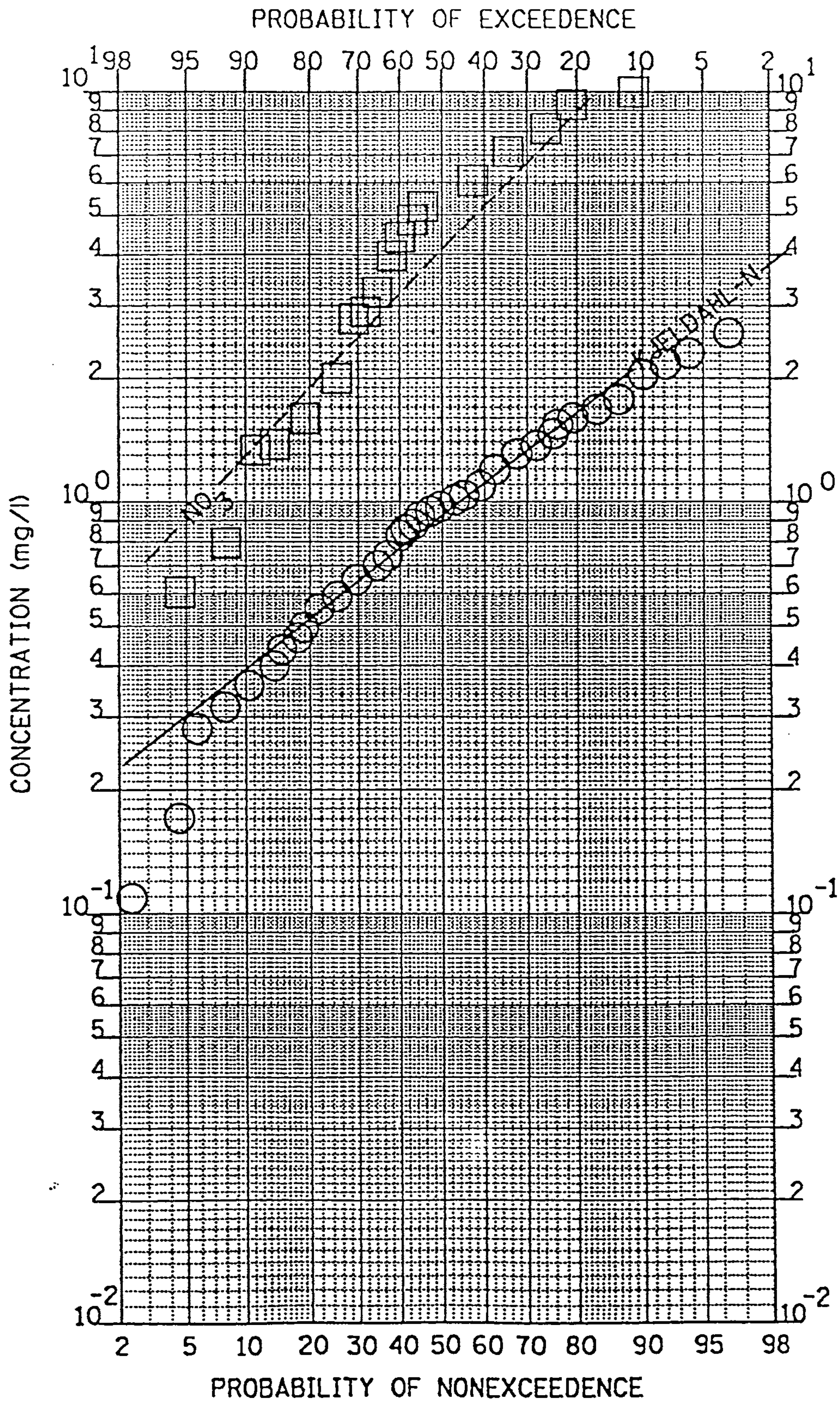

Figure 36. U.S.G.S. Gauge on Illinois River at Watts, Oklahoma

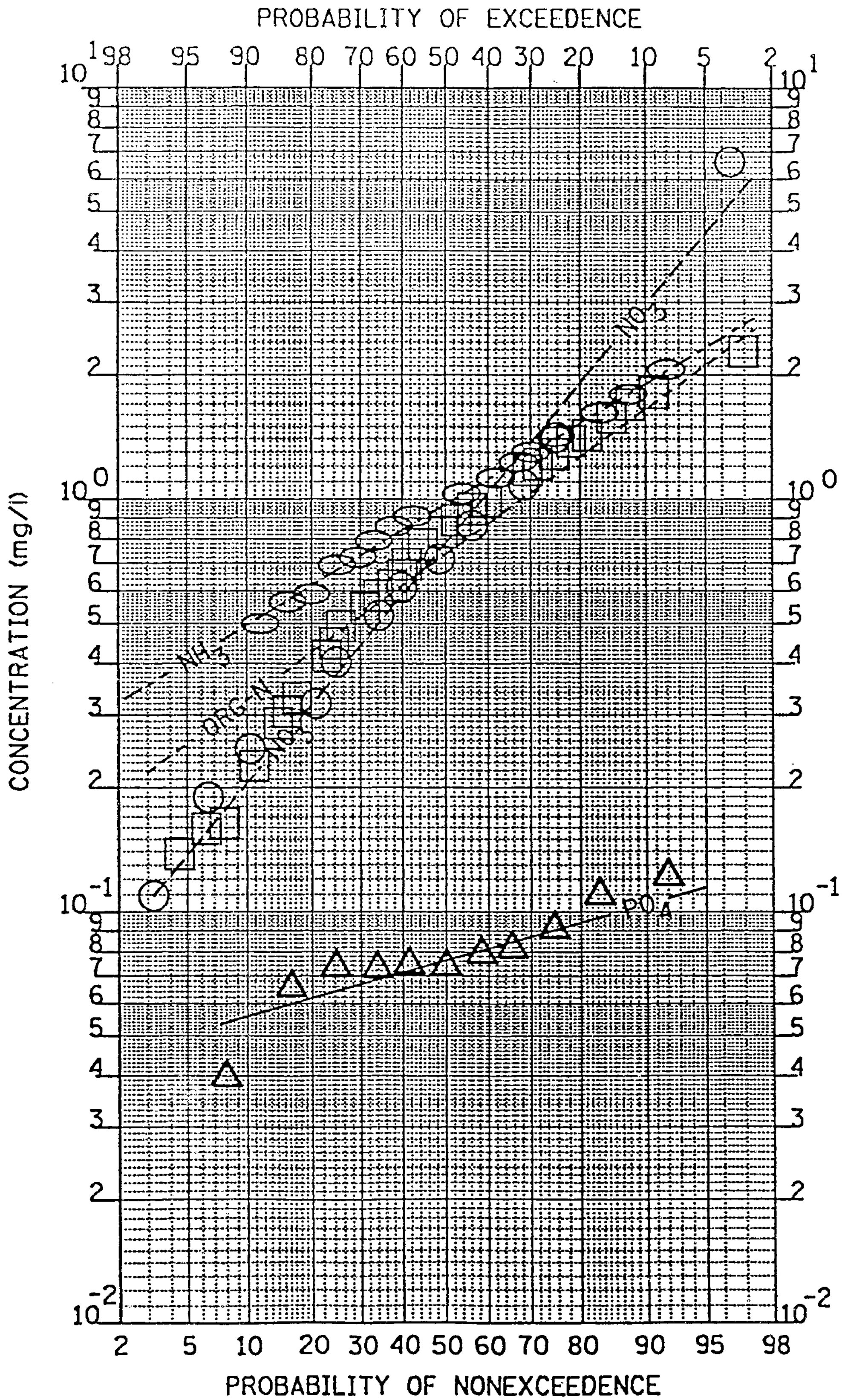

Figure 37. U.S.G.S. Gauge on Illinois River at Tahlequah, Oklahoma

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